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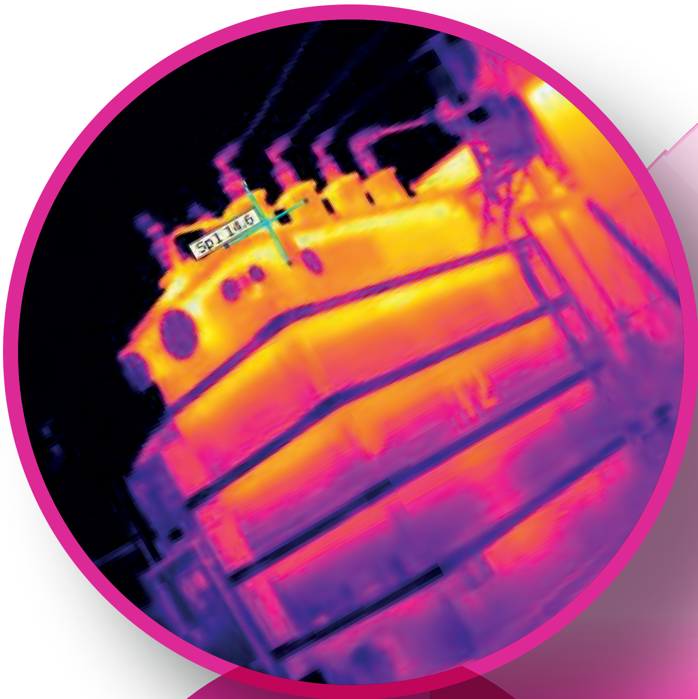

Transformer RTTR

- Prospects of applying RTTR to distribution transformers

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Task and objective:
Prospects of applying Real-time thermal rating to distribution transformers

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1 EXECUTIVE SUMMARY

Background

The Real-Time Thermal Rating (RTTR) project is part of Scottish Power Energy Networks (SPEN) LCNF Tier 2 project: Flexible Networks for a Low Carbon Future. Flexible Networks for a Low Carbon Future will provide the distribution network operators (DNO) 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. Dynamic rating should enable a contribution of 12% load increase in a safe way.

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, YockingsGate T1, LiverpoolRoad T1. In the context of the RTTR project DNV GL assessed the thermal behavior of these transformers using the loading guide as calculation model with the measured ambient temperature and load profiles. In particular, the following activities were performed:

- Collection and analysis of the available information
- Development of the thermal model
- Creating future load patterns, based on actual load patterns to simulate and verify a safe increase
    - by 8%, 10% and 12% of the actual load profiles
    - up to a peak at nameplate rating
    - up to an 8%, 10% and 12% on top of a peak at nameplate rating
    - up to a 15 years, 40 years and 60 years technical lifetime
- Creating future load patterns, based on actual load patterns and different levels load increase due to:
    - Charging of electrical vehicles
    - Generated solar energy
    - Installation of electrical heating.

Conclusions

From the analysis presented in this report, the following conclusions can be drawn:

1. All transformers are currently thermally low loaded
2. The temperature of the transformers is rather constant. This is due to the fact that the loading is highest in the winter when the ambient temperature is lowest and vice versa in the summer
3. Peak loadings can be increased above nameplate rating by 30-45% ensuring an expected technical lifetime of 40 years, given the situation in the current evaluation period and the parameters used in the model are sufficiently representative for the different transformers
4. With respect to integrating future loads coming from solar energy, electrical heating, electrical vehicles, etc., up to 15 MVA of additional peak loading can be allowed on top of the current load profiles
5. Close to the thermal limit, the ageing rate of the transformer increases rapidly and thus care should be taken when operating close to the thermal limit. The life time reduction increases significantly for hot spot temperatures above 120 $^{\circ}$C and considering the possible impact of the

hot spot factor on the hot spot temperature, it could be advised to limit the hot spot temperature. To prevent excessive ageing, RTTR is a very suitable means to provide support in the transformer loading so instead of flying blind, RTTR provides timely and accurate information as to the real thermal limit at any moment in real time

6 Using RTTR, full transparency regarding the decision to increase the loading can be provided to regulators and auditors
7 RTTR enhances confidence in the network operation and supports timely actions like load-shedding
8 Knowledge about possible loading capabilities of transformers, gathered with an RTTR system, can be used as input for short and long-term plans for the management of the SPEN network
9 Implementing RTTR results in significant higher profits if compared to the necessary implementation costs and additional costs for losses.

Recommendations

The following recommendations are given:

1 Due to the cyclic load pattern, the peak loading of the transformer can easily exceed the name plate rating without resulting in higher than nominal loss of life. To ensure the loss of life remains close to but below the nominal value, it is recommended to install a monitoring and real-time thermal rating system. Moreover, it is advised to take extra oil-samples during the verification tests after implementing RTTR to ensure no load-related internal defects become active.
2 From an efficiency and cost-reduction point-of-view, groups of similar transformers can be defined e.g. based on rating, manufacturer, age, location, etc. To accommodate thermal rating on such group only one thermal model is required reducing cost for software development and hardware. Investments cost can be divided over several transformers within each group.
3 It is recommended to perform a special test or heat run test as has been defined in /6/. Preferably this test needs to be done for each transformer to know its specific hotspots. To reduce costs, it could be decided to perform such a test once for each group of similar transformers, but then the accuracy for each specific transformer is lower.
4 If a heat run test cannot be performed, it is recommended to limit the hot spot temperature to account for possible deviations of the parameters given in the IEC used in the models from the actual values.

2 INTRODUCTION

2.1 Background

Scottish Power Energy Networks (SPEN) has received funding from the Low Carbon Networks Fund (LCNF). In particular SPEN is seeking ways to utilize the flexibility in their networks in order to increase and enhance the transport capability. As a result, the network can enable connections to low carbon technologies like wind and solar as well as heat pumps and charging of electrical vehicles. Moreover, energy efficiency encouraging program is done under specific large customers. Tools will be implemented in trial projects to demonstrate their effectiveness in reaching the research goals.

This project will help SPEN and other DNO's to evaluate network capacity using dynamic techniques. It aims to provide evidence of the capacity headroom available in existing networks that can be used before traditional network reinforcement needs to take place. This will enable networks to connect more customers and plan network reinforcement activities so that it happens only when genuinely needed.

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.

With respect to dynamic rating, in particular the transformer's life expectancy depends on the hot-spot temperature value. In particular, the transformer winding hot-spot temperature is critical for the ageing rate of the transformer insulation. The ageing rate is highest at the hot-spot and with that determines the life expectancy of the complete transformer as ageing of the paper insulation is an irreversible process.

2.2 Scope of work and activities performed

First part of the work consists of the condition assessment performed on 8 primary transformers:

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

The results from the condition assessment are described in DNV GL report 14-2132 "Real Time Thermal Rating System – Phase I Asset Condition Assessment" dated 14-07-2014 /5/. The main conclusions are as follows:

1. The estimated remaining lifetime of all 8 transformers that were part of the condition assessment is over 25 years
2. Due to the presence of free water in the oil samples taken ate Ruabon T1 and Whitchurch T1, DNV GL currently qualifies the following six transformers suitable for operating above their nameplate rating under careful dynamic loading:
    - St. Andrews T1 and T2
    - Cupar T1 and T2
    - Yockings Gate T1

- Liverpool Road T1.

Based on the successful implementation of the follow-up actions a recommended in /5/, Ruabon T1 and Whitchurch T1 can also be qualified. Therefore both transformers have been considered in this study as if there were no pending issues.

Due to this positive conclusion with respect to the condition of the transformers, the possibilities for operating transformers above nameplate rating is further investigated. This report describes the simulations performed to assess the capacity headroom for 8 primary transformers. Based on the study, the efficiency and effectiveness of applying transformer real-time thermal rating (RTTR) system will be discussed. In particular, the following activities were performed:

- Collection and analysis of the available information
- Development of the thermal model
- Creating future load patterns, based on actual load patterns:
    - Actual load pattern increased by 8%, 10% and 12%
    - Actual load pattern increased to a peak load of 21 MVA
    - 21 MVA load pattern increased by 8%, 10% and 12%
- Creating future load patterns, based on actual load patterns and different levels load increase due to:
    - Charging of electrical vehicles
    - Generated solar energy
    - Electrical heating.

2.3 Outline

In chapter 3, the starting points and approach of the project are briefly discussed. Chapters 4, 5 and 6 respectively discuss the thermal behaviour based on present load profiles, load profiles artificially increased to a peak at nameplate rating and based on nominal ageing to reach 15, 40 or 60 years of technical lifetime. In chapter 7 a brief sensitivity of three important parameters on the thermal behaviour is discussed. Chapter 8 discusses the impact of future loads. All results are summarized in chapter 9, discussing about transformer loading capabilities.

Chapter 10 continues with the added value of an RTTR system and finally chapter 11 gives overall conclusions and recommendations.

3 ASSESSMENT OF THE RTTR CAPABILITY OF ASSETS

Using the data obtained from SPEN and during the site visits, this chapter defines the starting point to evaluate the capability of the eight investigated transformers to adopt a Real Time Thermal Rating system.

3.1 Starting points

Besides the transformer details, loading profiles and ambient temperature profiles, the following starting points have been agreed:

1 The transformer can be considered as thermal bottleneck in the full feeder bay. In other words, the ratings of the switchgear, transformers, cables and lines are sufficient to accommodate higher loading of the transformers
2 If actual documents are missing, the starting points will be based on the standards or best practices from DNV GL
3 No significant changes in the transformers have been applied since the date of installation
4 The tap changers of the transformers are regulated automatically. The settings are not communicated to the control centre. Therefore it has been assumed that the tap changers are always in their nominal position
5 No clear information on failures and fault-through-currents was available and therefore the impact has been neglected
6 The insulation paper is not thermally upgraded
7 No dangerous hot-spots in winding, core frame structures and tanks are present
8 The artificial load patterns will be based on the actual load patterns in which the elevated peaks originating from failures of redundant circuits are removed by replacing the days containing peaks by data from the previous days
9 Because the calculation of the transformer hot-spot temperature is a difficult and complex task, the simplified calculations methods provided by IEC standards have been used:
    a. The heat sources, conductance's and capacitances are considered as concentrated elements instead of distributed elements
    b. The variation of oil viscosity with temperature is neglected
    c. Overshoot in hot-spot temperature is not considered
    d. Contaminations like moisture and air are not considered in the standard

    so that the temperatures calculated by IEC and IEEE models could be lower than in reality.
10 As discussed in /4/, the effect of moisture in the paper is significant. 2% moisture content in the paper could reduce the lifetime from 38 to less than 2 years at 90˚C. It was shown in /5/ that no significant moisture was present in the investigated transformers, except for Ruabon T1 and Whitchurch T1, which was recommended for further testing. Both conditions are further discussed in this report: 0% moisture content (expected lifetime 15 years at 98˚C) and 2% moisture content (expected lifetime 0.8 years at 98˚C).

In /10/ the following definitions are proposed and have been used throughout this report:

- Normal Life Expectancy Loading: Normal life expectancy occurs when a transformer is operated at 98° C continuously. The IEC recommends allowing the hot-spot temperature to reach 120° C for a short period during the day, provided the transformer will be operated for longer periods below 98° C.

- Planned Loading Beyond Nameplate: Where transformers do not carry steady continuous loads, which is the more typical utility operation, loading can be such that the hot-spot temperature can rise to 120° C. This operating scenario is intended for planned repetitive loads.

- Long-time Emergency Loading: In situations where a transformer is expected to carry emergency loads, the hot-spot temperature can rise to 140° C. This is not a normal operating condition and is expected to cover a prolonged outage (from several hours to several months) to some system element (single contingency outage). Expectation is that these types of events will occur only two or three times over the life of the transformer.
- Short-time Emergency Loading: For highly unlikely conditions (second and third contingencies) the hot-spot temperature can be allowed to go as high as 180° C. This would be expected to occur for a short period (two to three hours) and only once or twice over the life of the transformer.

3.2 Transformer details

The details of the different transformers that have been used in the transformer model have been gathered. This section summarizes the details for transformer T1 located at substation St. Andrews. Appendix A shows the data used for all transformers.

General	
Supplier	Bruce Peebles
Year of manufacturing	1966
Serial number	43546
Cooling	ONAF/ONAN
Power	
Nominal power (ONAF)	21 MVA
Nominal power (ONAN)	15 MVA
Voltage	
Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV
Current	
Nominal primary current (ONAF)	367.5 A
Nominal primary current (ONAN)	262.5 A
Nominal secondary current (ONAF)	1103 A
Nominal secondary current (ONAN)	788 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transformer in the thermal model.

– Nominal values for the current

• Primary winding	I_{ONAN}	262.5 A	I_{ONAF}	367.5 A
• Secondary winding	I_{ONAN}	788.0 A	I_{ONAF}	1103.0 A

– Nominal values for the power

• Primary winding	P_{ONAN}	15 MVA	P_{ONAF}	21 MVA
• Secondary winding	P_{ONAN}	15 MVA	P_{ONAF}	21 MVA

- Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV U_{ONAF} 33 kV
  - Secondary winding U_{ONAN} 11 kV U_{ONAF} 11 kV

- Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6 R_{ONAF} 6
  - Secondary winding R_{ONAN} 6 R_{ONAF} 6

- Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN/ONAF

- Transition winding temperatures ONAN – ONAF and ONAF – ONAN
  - Transition from ONAN to ONAF $\Theta_{ONAN-ONAF}$ 75 °C
  - Transition from ONAF to ONAN $\Theta_{ONAF-ONAN}$ 50 °C

- Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
  - ONAF mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$

- Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
  - ONAN mode τ_{oil} = 210 min, $\tau_{winding}$ = 10 min
  - ONAF mode τ_{oil} = 150 min, $\tau_{winding}$ = 7 min

- Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode $x = 0.8$, $y = 1.3$
  - ONAF mode $x = 0.8$, $y = 1.3$

- Sample time for actual values for current and ambient temperature
  - t_{sample} = 900 s (15 minutes)

- Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
  - ONAN mode $(H{\cdot}g_r)_{ONAN}$ = 26 °C
  - ONAF mode $(H{\cdot}g_r)_{ONAF}$ = 26 °C.

3.3 Load and temperature profiles

To predict the RTTR profile for each transformer, including estimation on the predicted rating uplift for each transformer, the following simulations will be performed:

1. The base-case has been determined, in which the transformer hot-spot temperature has been simulated as function of the actual measured ambient temperature profile and load profile averaged over the three-year period from 2011 till 2013.
2. Using this base-case, the load has been increased with 8%, 10% and 12%, assuming a similar load pattern and ambient temperature profile.
3. The load has been increased to reach a peak load corresponding to the transformer rating. So 21 MVA in case of St. Andrews T1 and T2 and Cupar T1 and T2, 10 MVA in case of Ruabon T1 and Whitchurch T1 and 7.5 MVA in case of Yockingsgate T1 and Liverpoolroad T1.
4. The 8%, 10% and 12% rating uplift for each transformer is estimated.

5 Finally, the maximum loading increase that each transformer can safely achieve is determined, referring to the transformers end-of-life: 15, 40 or 60 years of remaining life.

Chapter 4 discusses the base-case and increased load-profiles by 8%, 10% and 12% (items 1 and 2). It is shown that all transformers are currently operated well within their capability and that room is available to further increase the load. This will be further explored in chapter 5, in which items 3 and 4 are further investigated. Finally chapter 6 discusses the impact of further increasing the rating above the nameplate rating on the life-expectancy.

3.4 Ambient temperature

The ambient temperature profiles have been taken from one location, in particular Leuchars, for the transformers in the Northern region (St. Andrews T1 and T2, Cupar T1 and T2) and one location, in particular Hawarden, for the transformers in the Southern region (Ruabon T1, Whitchurch T1, Yockingsgate T1, Liverpoolroad T1). The temperature profiles are shown in Figure 3-1 respectively Figure 3-2.

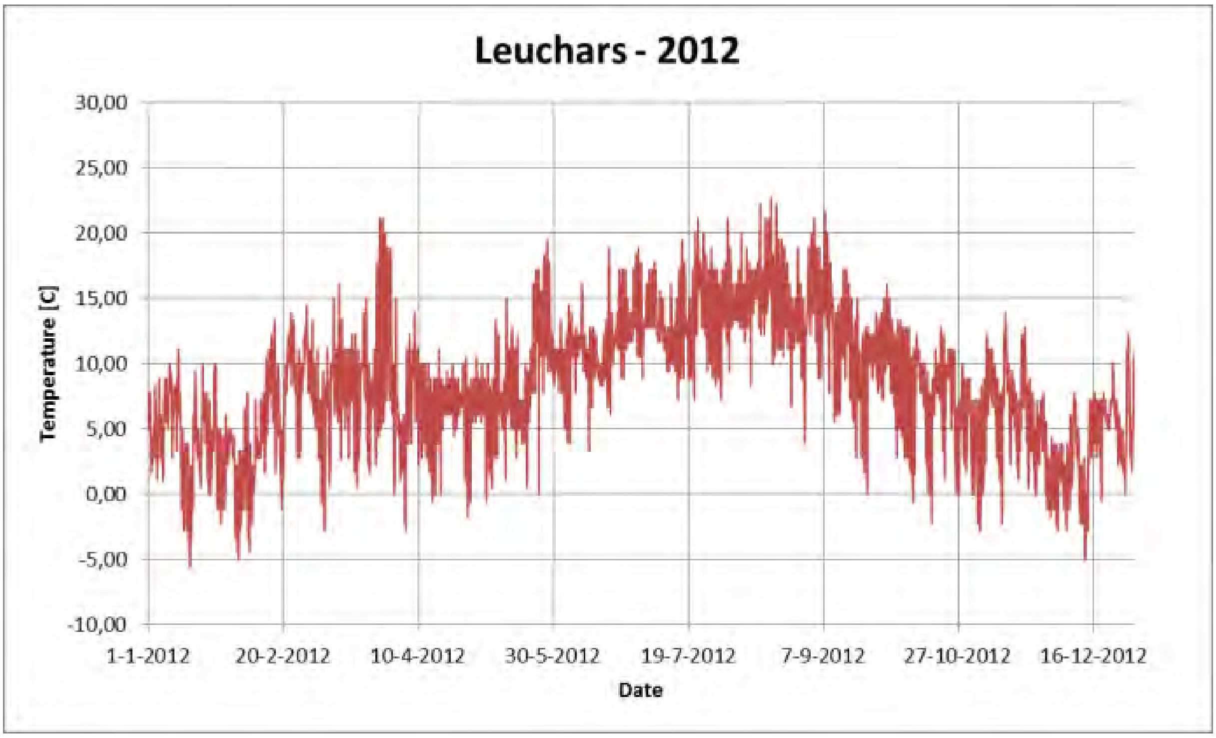


Figure 3-1: Ambient temperatures profile the transformers St. Andrews T1, St. Andrews T2, Cupar T1 and Cupar T2.

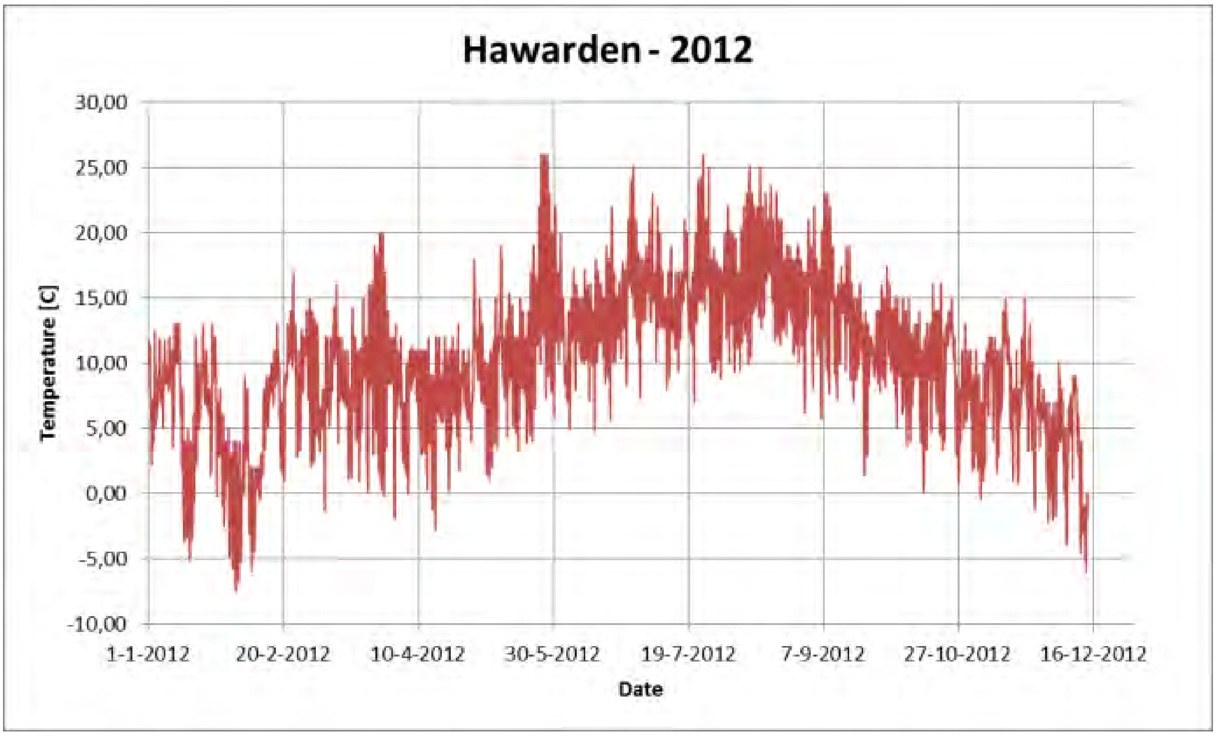


Figure 3-2: Ambient temperatures profile the transformers Ruabon T1, Whitchurch T1, Yockingsgate T1 and Liverpoolroad T1.

4 THERMAL BEHAVIOUR BASED ON PRESENT LOAD PROFILES

In this chapter, the thermal response of the eight selected transformers will be assessed, based on their present load profiles averaged over 2011-2013 and temperature profile of 2012. The peaks in the load profiles originating from service outages of redundant transformers are smoothened by replacing this peak load data by the normal load data of the preceding day(s).

The impact of an overall increase of 8%, 10% and 12% of the present load profile on the thermal behaviour is assessed as well. This increased load profile is created by increasing all data points of the present load profile by 8%, 10% respectively 12%.

4.1 St. Andrews T1

The averaged load profile from 2011-2013 as shown in Figure 4-1 has been used in the model to determine the thermal behaviour of transformer T1 at substation St. Andrews. The hotspot and top oil temperature as function of time is shown in Figure 4-2.

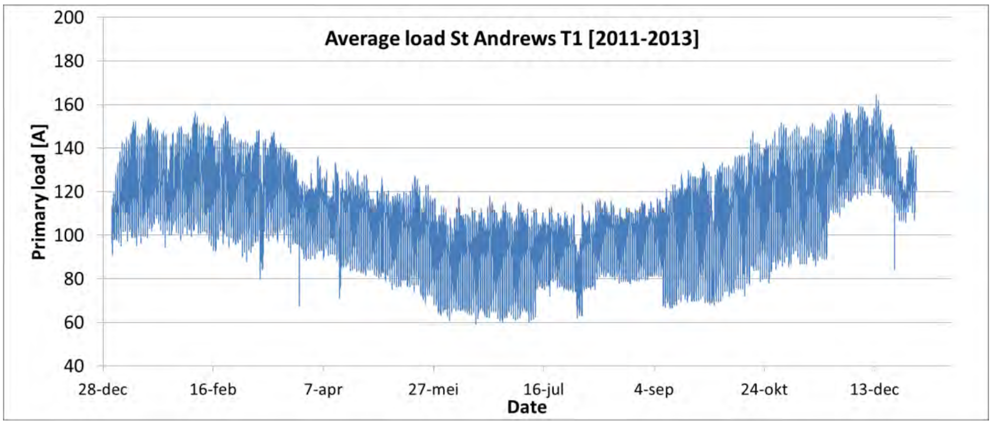


Figure 4-1: Load profile of St. Andrews T1

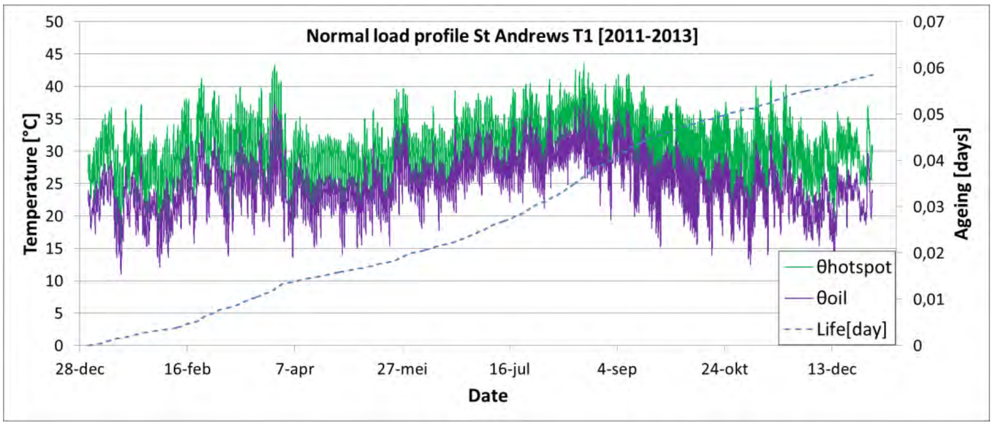


Figure 4-2: Hotspot and oil temperature profile and ageing as function of time of transformer T1 at substation St. Andrews, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-1. It can be concluded that the hotspot temperature stays well below the allowed 98˚C.

Table 4-1: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 21 MVA)

Load relative to current load profile (MVA)	Top oil temperature [˚C]	Winding temperature [˚C]	Hotspot temperature [˚C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (9,4 MVA)	37	41	43
1.08 (10,1 MVA)	38	42	44
1.10 (10,3 MVA)	38	43	44
1.12 (10,5 MVA)	38	43	45

4.2 St. Andrews T2

The averaged load profile from 2011-2013 as shown in Figure 4-3 has been used in the model to determine the thermal behaviour of transformer T2 at substation St. Andrews. The hotspot and top-oil temperature as function of time is shown in Figure 4-4.

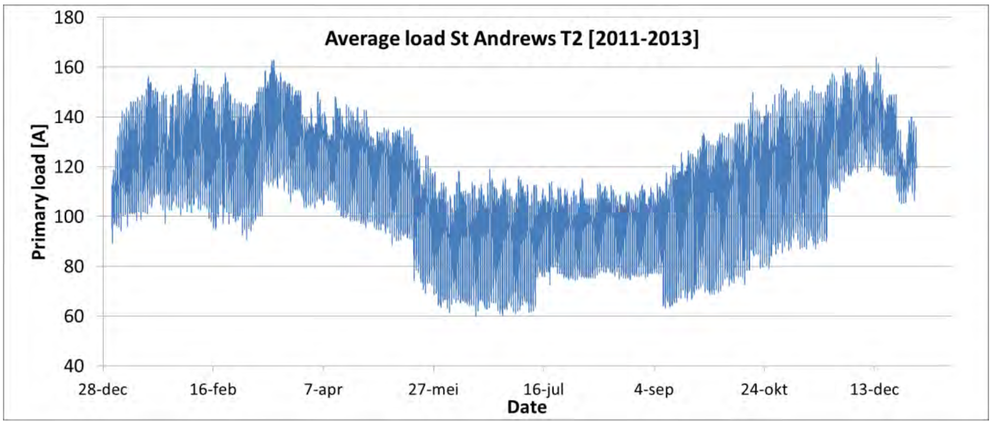


Figure 4-3: Load profile of St. Andrews T2

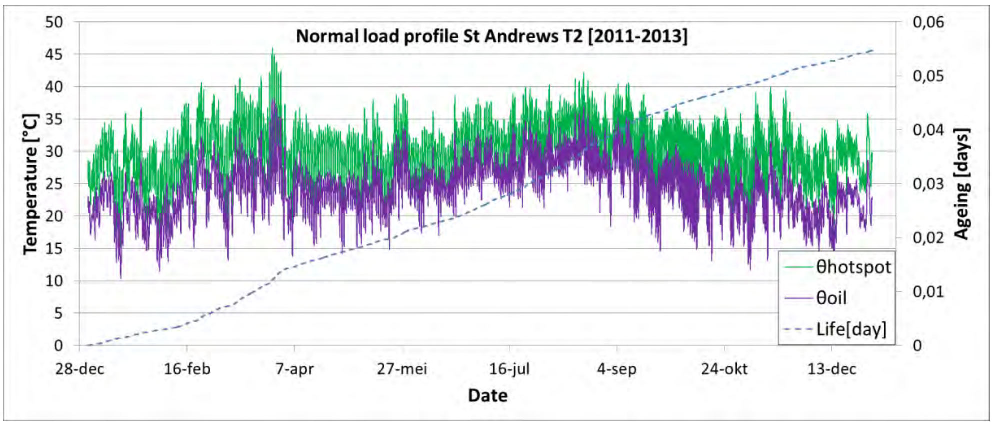


Figure 4-4: Hot-spot and oil temperature profile and ageing as function of time of transformer T2 at substation St. Andrews, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-2. It can be concluded that the hotspot temperature stays well below the allowed 98°C.

Table 4-2: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 21 MVA)

Load relative to current load profile (MVA)	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (9,4 MVA)	38	44	46
1.08 (10,1 MA)	39	46	48
1.10 (10,3 MVA)	40	46	49
1.12 (10,5 MVA)	40	47	49

4.3 Cupar T1

The averaged load profile from 2011-2013 as shown in Figure 4-5 has been used in the model to determine the thermal behaviour of transformer T1 at substation Cupar. The hotspot and top-oil temperature as function of time is shown in Figure 4-6.

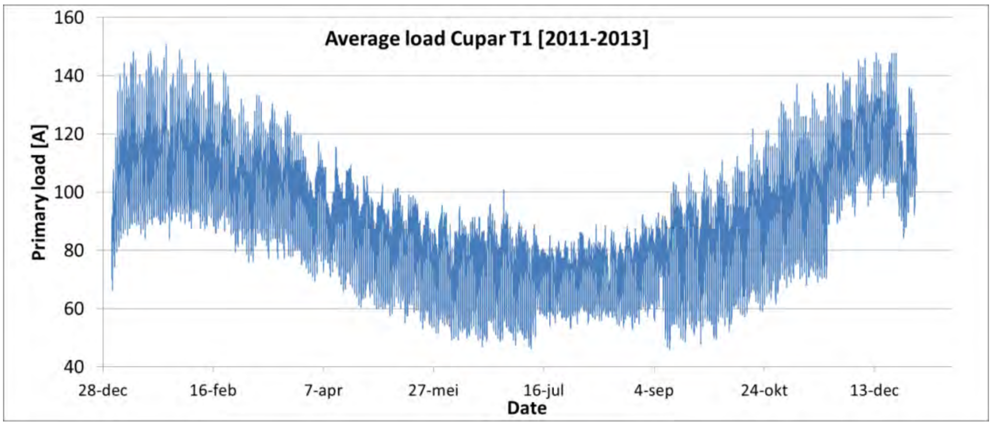


Figure 4-5: Load profile of Cupar T1

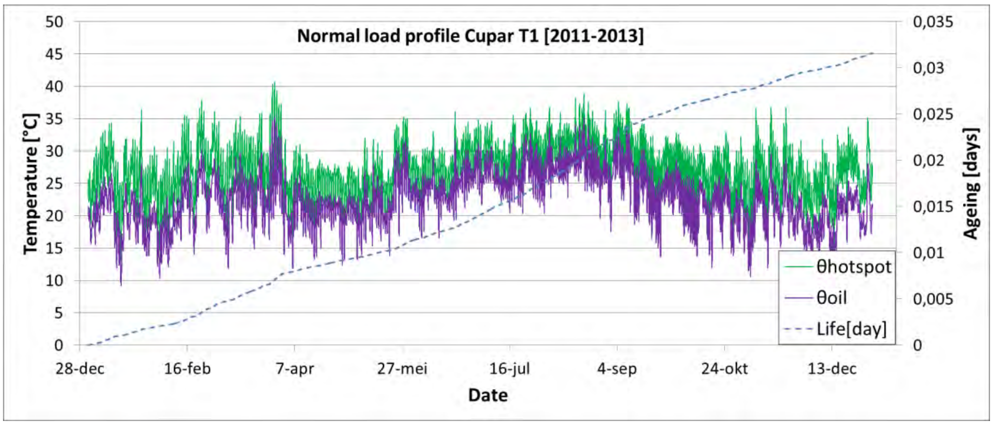


Figure 4-6: Hot-spot and oil temperature profile and ageing as function of time of transformer T1 at substation Cupar, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-3. It can be concluded that the hotspot temperature stays well below the allowed 98°C.

Table 4-3: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 21 MVA)

Load relative to current load profile (MVA)	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (8,6 MVA)	35	39	41
1.08 (9,3 MVA)	36	41	42
1.10 (9,5 MVA)	36	41	42
1.12 (9,7 MVA)	36	41	43

4.4 Cupar T2

The averaged load profile from 2011-2013 as shown in Figure 4-7 has been used in the model to determine the thermal behaviour of transformer T2 at substation Cupar. The hotspot and top-oil temperature as function of time is shown in Figure 4-8.

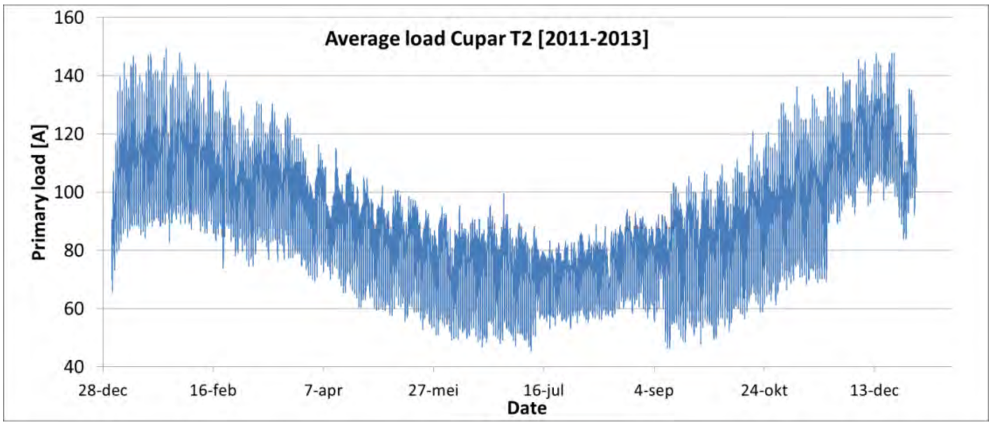


Figure 4-7: Load profile of Cupar T2

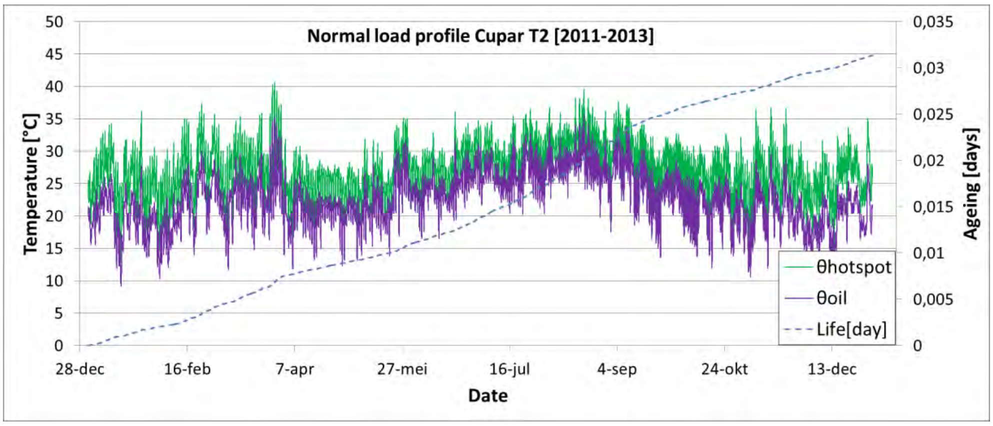


Figure 4-8: Hot-spot and oil temperature profile and ageing as function of time of transformer T2 at substation Cupar, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-4. It can be concluded that the hotspot temperature stays well below the allowed 98°C.

Table 4-4: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 21 MVA)

Load relative to current load profile (MVA)	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (8,5 MVA)	35	39	41
1.08 (9,2 MVA)	36	40	42
1.10 (9,4 MVA)	36	41	42
1.12 (9,6 MVA)	36	41	42

4.5 Ruabon T1

The averaged load profile from 2011-2013 as shown in Figure 4-9 has been used in the model to determine the thermal behaviour of transformer T1 at substation Ruabon. The hotspot and top-oil temperature as function of time is shown in Figure 4-10.

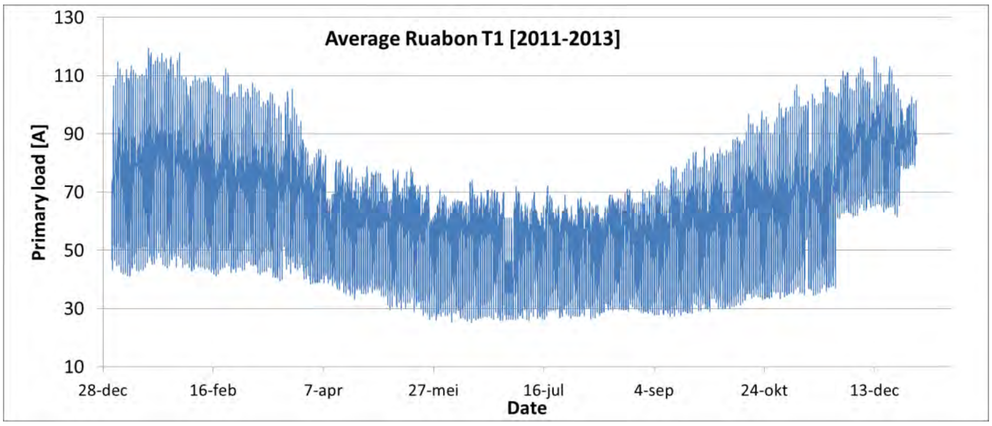


Figure 4-9: Load profile of Ruabon T1

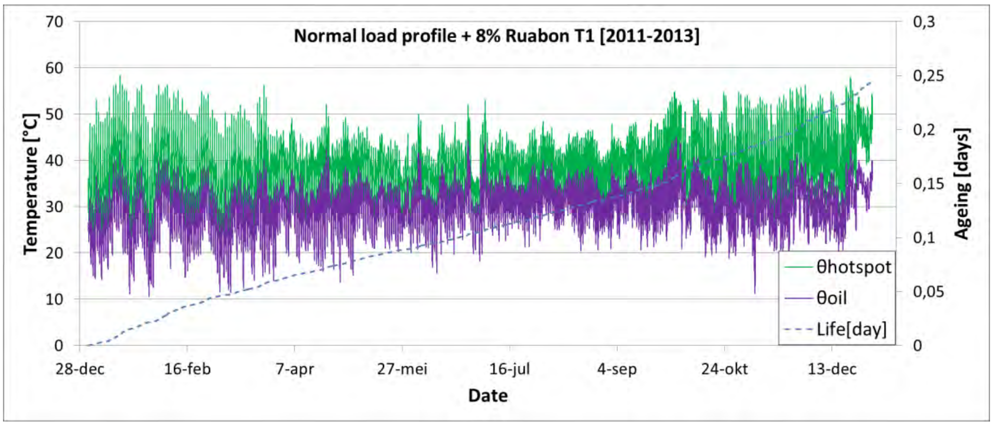


Figure 4-10: Hot-spot and oil temperature profile and ageing as function of time of transformer T1 at substation Ruabon, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-5. It can be concluded that the hotspot temperature stays well below the allowed 98°C.

Table 4-5: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 10 MVA)

Load relative to current load profile (MVA)	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (6,8 MVA)	44	51	54
1.08 (7,4 MVA)	45	54	58
1.10 (7,5 MVA)	45	55	59
1.12 (7,6 MVA)	46	56	60

4.6 Whitchurch T1

The averaged load profile from 2011-2013 as shown in Figure 4-11has been used in the model to determine the thermal behaviour of transformer T1 at substation Whitchurch. The hotspot and top-oil temperature as function of time is shown in Figure 4-12.

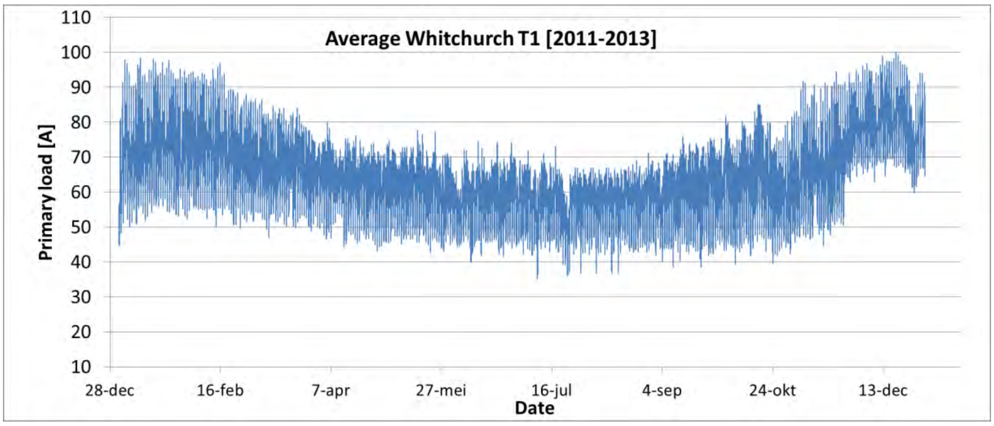


Figure 4-11: Load profile of Whitchurch T1

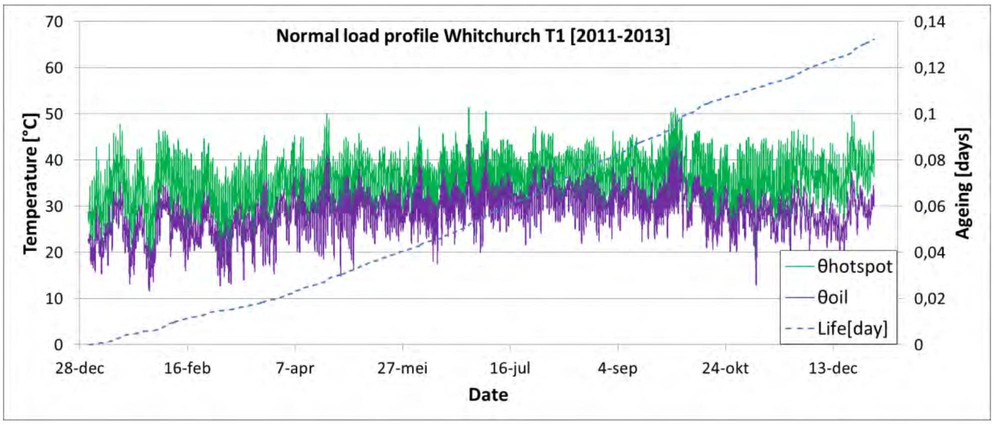


Figure 4-12: Hot-spot and oil temperature profile and ageing as function of time of transformer T1 at substation Whitchurch, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-6. It can be concluded that the hotspot temperature stays well below the allowed 98°C.

Table 4-6: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 10 MVA)

Load relative to current load profile (MVA)	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (5,7 MVA)	44	50	51
1.08 (6,2 MVA)	45	51	53
1.10 (6,3 MVA)	45	52	54
1.12 (6,4 MVA)	45	52	55

4.7 Yockingsgate T1

The averaged load profile from 2011-2013 as shown in Figure 4-13 has been used in the model to determine the thermal behaviour of transformer T1 at substation Yockingsgate. The hotspot and top-oil temperature as function of time is shown in Figure 4-14.

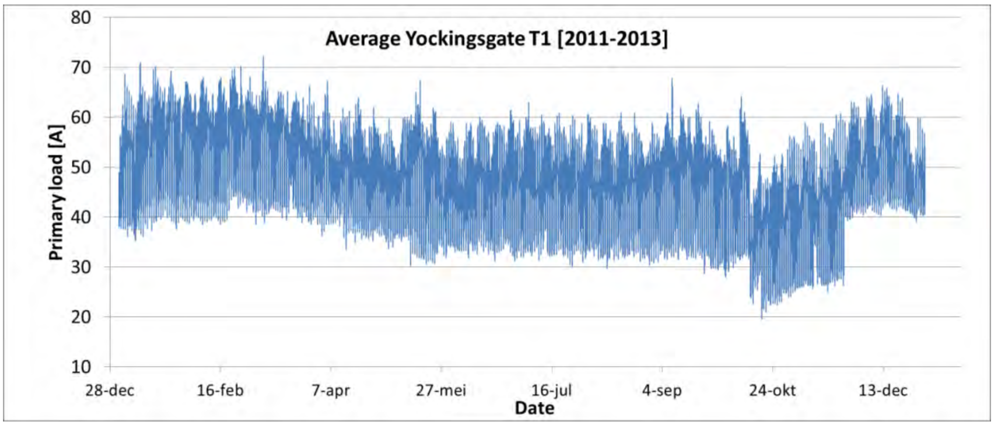


Figure 4-13: Ambient temperature profile (left) and load profile (right) from 2012 of Whitchurch T1

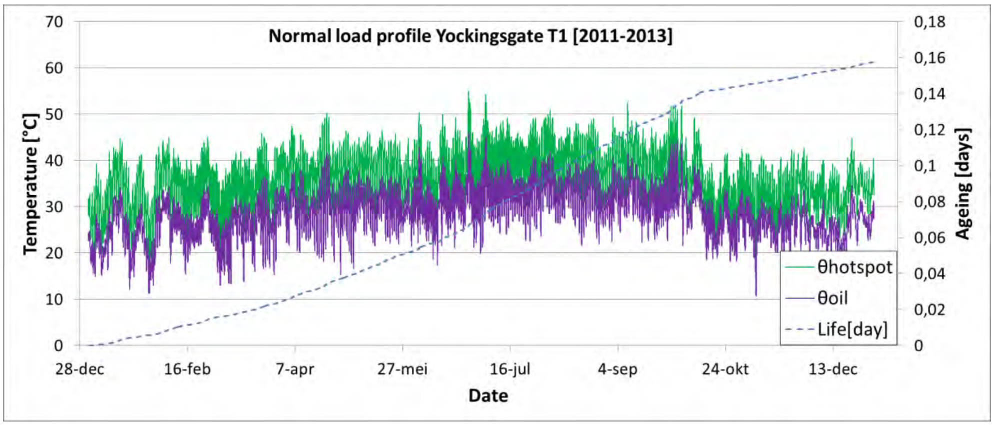


Figure 4-14: Hot-spot and oil temperature profile and ageing as function of time of transformer T1 at substation Yockingsgate, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-7. It can be concluded that the hotspot temperature stays well below the allowed 98°C.

Table 4-7: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 7,5 MVA)

Load relative to current load profile (MVA)	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (4,1 MVA)	46	53	55
1.08 (4,5 MVA)	47	55	57
1.10 (4,5 MVA)	47	55	57
1.12 (4,6 MVA)	48	56	59

4.8 Liverpoolroad T1

The averaged load profile from 2011-2013 as shown in Figure 4-15 has been used in the model to determine the thermal behaviour of transformer T1 at substation Liverpoolroad. The hotspot and top-oil temperature as function of time is shown in Figure 4-16.

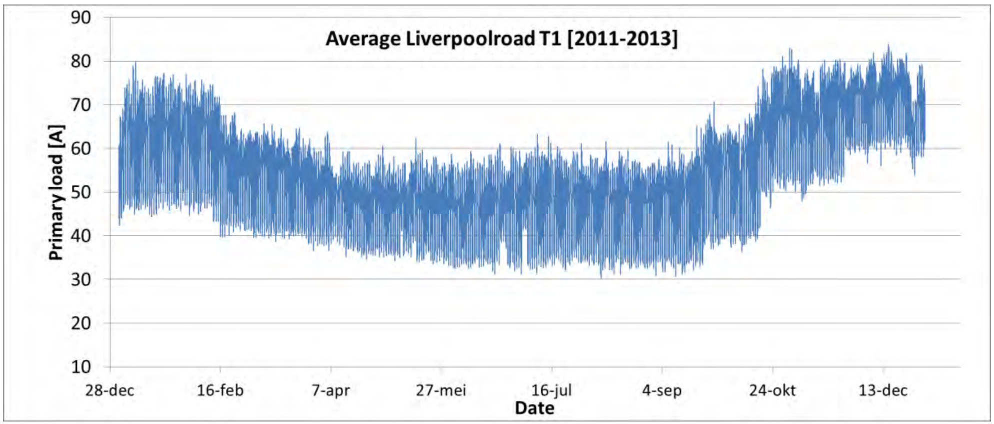


Figure 4-15: Load profile of Liverpoolroad T1

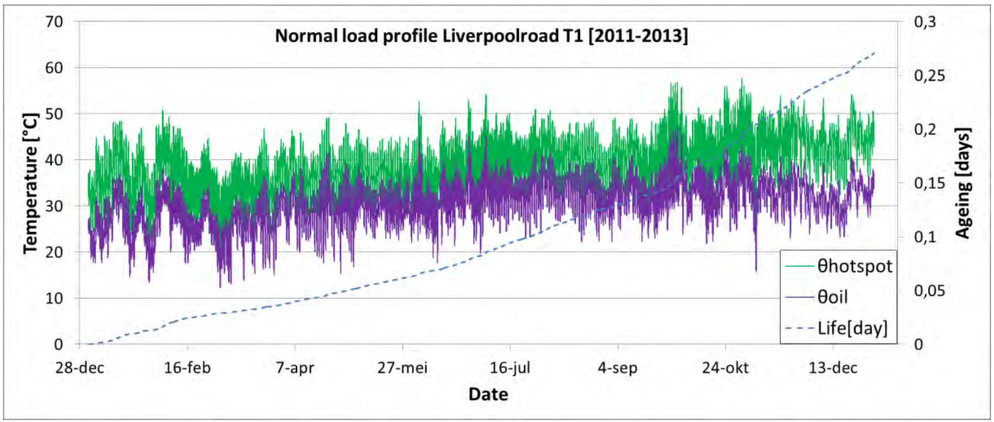


Figure 4-16: Hot-spot and oil temperature profile and ageing as function of time of transformer T1 at substation Liverpoolroad, based on the ambient temperature and averaged load profile

The results of the 8%, 10% and 12% load increase are shown Table 4-8. It can be concluded that the hotspot temperature stays well below the allowed 98°C.

Table 4-8: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile (rating 7,5 MVA)

Load relative to current load profile (MVA)	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**n/a**	**≤140**
1 (4,8 MVA)	47	55	58
1.08 (5,2 MVA)	49	58	62
1.10 (5,3 MVA)	49	59	63
1.12 (5,4 MVA)	50	60	64

4.9 Summary and conclusions

Based on the simulations presented in this chapter it can be concluded that the transformers are currently operated well within their thermal capability. This is due to the fact that the peak load is only 40-68% of the nameplate rating. The results have been summarized in Table 4-10, including the thermal limits recommended by the IEC 60076 standards. Comparing the results from the simulations with the thermal limits it is clear that the internal temperatures are well below the provided limits. Considering:

- the Arrhenius rule of thumb, which says that the ageing rate doubles or halves with every 6°C temperature increase respectively decrease, according to $V = 2^{\frac{\theta_h - 98}{6}}$, in which V is the relative ageing rate /1/ and
- that according to table 1 shown in the IEC 60076-7 /1/, the nominal ageing rate at 98°C leads to 15 years of continuous operating life

this means that thermal ageing due to loading of the transformers is typically low. This confirms the results discussed in /5/ and summarized in Table 4-9 which shows that all transformers have not aged at all.

Table 4-9: Actual lifetime reduction (assuming similar load profile as current during the past) and actual age of the eight investigated transformers

Transformer	Real use [year]	Actual age [year]
St. Andrews T01	0,3	48
St. Andrews T02	0,3	48
Cupar T1	0,1	48
Cupar T2	0,1	48
Ruabon T1	0,0	1
Whitchurch T1	0,0	4
YockingsGate T1	1,1	50

Transformer failure mechanisms are generally from mechanical, constructional or environmental ageing instead of thermal ageing. In particular, abnormal events such as over voltages and systems faults are much more detrimental than long-term ageing. Other ageing mechanisms are coming from excessive vibrations, winding distortion, failure of leads supports and clamping, integrity of the transformer tank, contaminations, etc. More details can be found in /7/ and /8/.

It can be concluded that room is available to investigate further increase of the transformer load, using the typical given load-profile, typically to reach at least the nameplate rating and if possible above. This will be studied in chapter 5.

Table 4-10: Top oil, winding and hotspot temperature as function of the load increase relative to the actual load profile

Load relative to current load profile	Ratio load and name plate rating	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**n/a**	**≤105**	**n/a**	**≤140**
1	0,40-0,68	44-47	50-55	51-58
1.08	0,44-0,74	45-49	51-58	53-62
1.10	0,45-0,75	45-49	52-59	54-63
1.12	0,46-0,76	45-50	52-60	55-64

5 THERMAL BEHAVIOUR BASED ON RATED LOAD PROFILES

From chapter 4 it was concluded that under the present load profiles, all transformers are relatively low loaded, from a thermal point of view. Amongst other things, the load profile is strongly influenced by the redundancy in the grid. Therefore it is interesting to see if the transformers can operate at rated load profile in case of contingency situations.

Operating the transformer at nameplate rating typically means operating the transformer at a winding temperature of 85 °C or at a hotspot temperature of 98°C /2/. From the actual loading profiles it became clear from the simulations described in chapter 4 that the transformers never operate at a constant loading leading to a constant hotspot temperature of 98°C. Therefore, this chapter investigates the thermal profiles of the transformers at rated peak load. For that purpose, the present load profiles are increased until the peak value reaches the rated current. Moreover, the rated load is further increased by 8%, 10% and 12% to investigate available head space in the loading of the transformers.

The first section provides an example of the procedure for transformer T1 at St. Andrews. The second section summarizes all results for all transformers followed by a section with a set of conclusions.

5.1 St. Andrews T1

The actual load profile has been artificially increased to reach a peak at rated power, for the same load pattern. In the case of St. Andrews T1 this means 21 MVA or 367.5 A, see Figure 5-1.

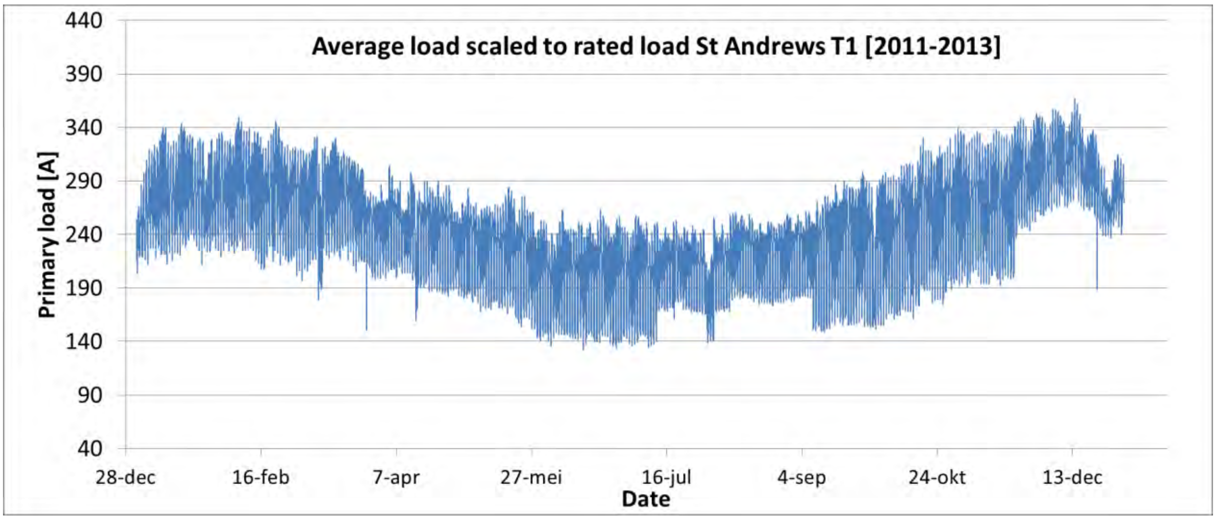
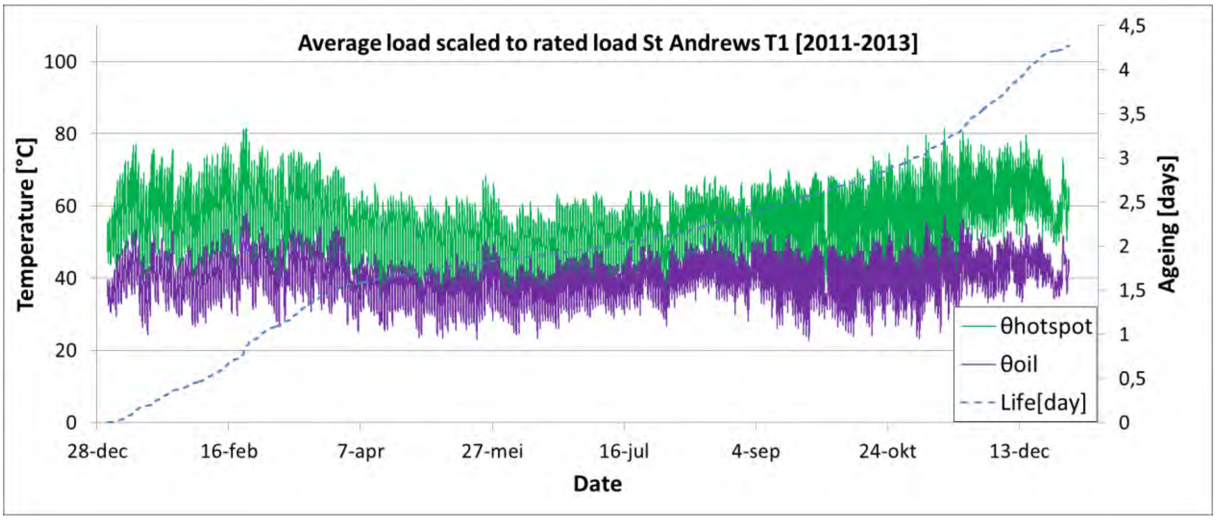


Figure 5-1: Artificial load profile increased to rated peak load based on actual load pattern

Moreover, the load profile was further increased by 8%, 10% and 12% above rated current. The temperature profiles at rated current and 12% above rated current are shown in Figure 5-2.



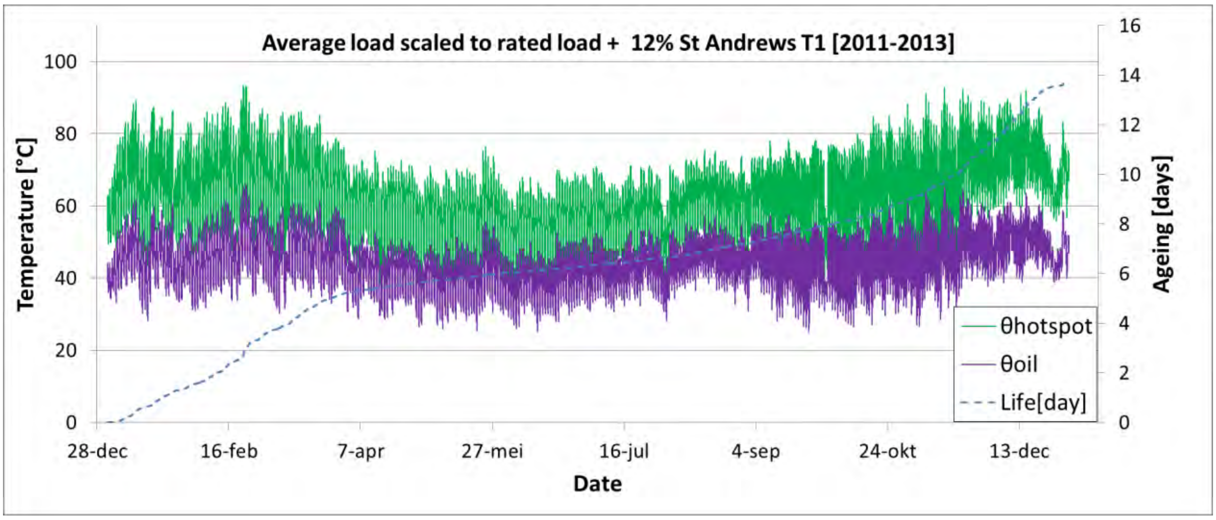


Figure 5-2: Temperature profiles with a peak loading of 21 MVA (top) and 21 MVA + 12% (bottom) without exceeding a hot-spot temperature of 98 ºC

The results of the 8%, 10% and 12% load increase on top of a peak loading of 21 MVA are shown Table 5-1. It can be concluded that the hotspot temperature still stays below the allowed 98°C. Moreover, the lifetime reduction per year is only a couple of days at rated peak load but rapidly increasing to 14 days at 12% load increase. Based on these values, it can be concluded that the expected life-time of the transformers is exceeding the required design life of 40 to 60 years.

Table 5-1: Maximum top oil, winding and hotspot temperature and lifetime reduction per year as function of the load increase relative to the rated peak load profile

Load relative to current load profile	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]	Lifetime reduction per year [days]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**	**n/a**
IEC 60076-7 (higher loading)	**≤105**	**≤120**	**≤140**	**n/a**
1	58	76	82	4
1.08	63	83	89	9
1.10	65	85	91	11
1.12	66	87	93	14

5.2 Summary and conclusions

In a similar way, the maximum top oil, winding and hotspot temperature and lifetime reduction per year has been estimated for the other transformers. The results are summarized in the following tables. Table 5-2 shows that with a load profile with a peak at rated power, the maximum temperatures stay well within the limits given in the IEC. Moreover, the lifetime reduction is only a couple of days per year.

Table 5-2: Maximum top oil, winding and hotspot temperature and lifetime reduction per year at rated peak load profile for all studied transformers

Load relative to current load profile	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]	Lifetime reduction per year [days]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**	**n/a**
IEC 60076-7 (higher loading)	**≤105**	**≤120**	**≤140**	**n/a**
St. Andrews T1	58	76	82	4
St. Andrews T2	64	81	87	6
Cupar T1	57	78	84	2
Cupar T2	57	78	84	2
Ruabon T1	56	73	79	2
Whitchurch T1	60	80	86	3
Yockingsgate T1	63	81	87	6
Liverpoolroad T1	63	83	89	6

Table 5-3, Table 5-4 and Table 5-5 show the impact of increasing the load profiles by an additional 8%, 10% and 12%. The 8% increased load profile still shows values below the 98°C, but the 10% and 12% increased load profiles give maximum temperatures exceeding the continuous loading temperatures. Still the temperatures fall within the limits for temporary higher loading (emergency loading). As a consequence higher than nominal ageing occurs during small periods of time but lifetime reduction over one year is still not very significant. It can be concluded that in case of contingency, the transformers can be loaded 12% above nameplate rating (peak rating), considering the present load profile.

Further increase in the loading will therefore be discussed in the next chapter, taking certain transformer life expectations into account.

Table 5-3: Maximum top oil, winding and hotspot temperature and lifetime reduction per year at rated peak load profile increased by 8% for all studied transformers

Load relative to current load profile	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]	Lifetime reduction per year [days]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**	**n/a**
IEC 60076-7 (higher loading)	**≤105**	**≤120**	**≤140**	**n/a**
St. Andrews T1	63	83	89	9
St. Andrews T2	69	88	94	14
Cupar T1	63	86	93	5
Cupar T2	63	86	93	5
Ruabon T1	61	80	87	4
Whitchurch T1	65	87	94	7
Yockingsgate T1	67	88	94	12
Liverpoolroad T1	68	90	97	13

Table 5-4: Maximum top oil, winding and hotspot temperature and lifetime reduction per year at rated peak load profile increased by 10% for all studied transformers

Load relative to current load profile	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]	Lifetime reduction per year [days]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**	**n/a**
IEC 60076-7 (higher loading)	**≤105**	**≤120**	**≤140**	**n/a**
St. Andrews T1	65	85	91	11
St. Andrews T2	70	90	96	17
Cupar T1	64	87	95	6
Cupar T2	64	88	95	6
Ruabon T1	62	82	90	4
Whitchurch T1	67	89	96	8
Yockingsgate T1	67	89	96	14
Liverpoolroad T1	69	92	99	16

Table 5-5: Maximum top oil, winding and hotspot temperature and lifetime reduction per year at rated peak load profile increased by 12% for all studied transformers

Load relative to current load profile	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]	Lifetime reduction per year [days]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**	**n/a**
IEC 60076-7 (higher loading)	**≤105**	**≤120**	**≤140**	**n/a**
St. Andrews T1	66	87	93	14
St. Andrews T2	71	92	98	21
Cupar T1	66	89	97	7
Cupar T2	66	90	97	7
Ruabon T1	63	84	92	5
Whitchurch T1	68	91	98	9
Yockingsgate T1	70	91	97	17
Liverpoolroad T1	70	94	101	20

6 THERMAL BEHAVIOUR BASED ON NOMINAL AGEING

From the previous chapter it became clear that even loading up to the rated peak load the transformers are not significantly thermally aged. Moreover, additional 12% loading can be applied without significant thermal ageing.

As was shown in the report on the condition assessment the actual lifetime reduction of the eight investigated transformers based on the loading guide is very small /5/. The details are summarized in Table 6-1 and it can be concluded that all transformers have not aged at all.

Table 6-1: Actual lifetime reduction (assuming similar load profile as current during the past) and actual age of the eight investigated transformers

Transformer	Real use [year]	Actual age [year]
St. Andrews T01	0,3	48
St. Andrews T02	0,3	48
Cupar T1	0,1	48
Cupar T2	0,1	48
Ruabon T1	0,0	1
Whitchurch T1	0,0	4
YockingsGate T1	1,1	50

In this chapter the load will be further increased until a 15 years, 40 years or 60 years transformer life is reached. As discussed in the previous chapter, nominal ageing of paper at 98°C results in a life time of the paper of 15 years. So if the transformer is designed to continuously operate at 98°C, the design life of the transformer would be 15 years. Generally, transformers are expected to operate for at least 40 to 60 years. The rating uplift for 15, 40 and 60 years of operational life will be simulated, which means 365 days lifetime reduction per year in case of 15 years operational life, 137 days of lifetime reduction per year in case of 40 year operational life and 91 days of lifetime reduction per year in case of 60 years operation life.

The first section provides an example of the procedure for transformer T1 at St. Andrews. The second section summarizes all results for all transformers followed by a section with a set of conclusions.

6.1 St. Andrews T1

The actual load profile has been artificially increased to reach a lifetime reduction per year as mentioned in the introduction.

To reach an expected life of 15 years, the transformer load can be increased peaking at 531 A or 30,4 MVA. Under these operating conditions, the maximum temperatures are significantly higher than the values given in the IEC 60076-2, see Figure 6-1. In particular the hotspot temperature during the winter period indicates probability for bubble formation leading to an early failure of the transformer.

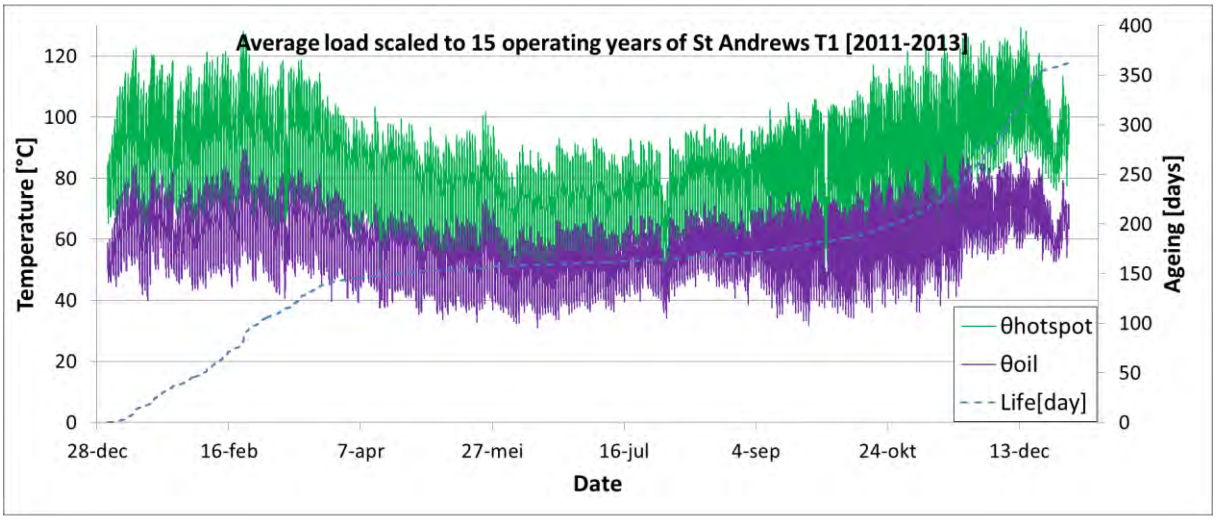


Figure 6-1: Temperature profiles with a peak loading of 30,4 MVA to reach a maximum lifetime of 15 years

To reach an expected life of 40 years, the transformer load can be increased peaking at 493 A or 28,1 MVA. Under these operating conditions, the maximum temperatures are significantly higher than the values given in the IEC 60076-2, see Figure 6-2. However, the maximum temperatures are lower than the values given in the IEC 60076-7 as limits applicable to loading beyond nameplate rating. For short time emergency loading, it can be concluded that temperatures are within the given limits.

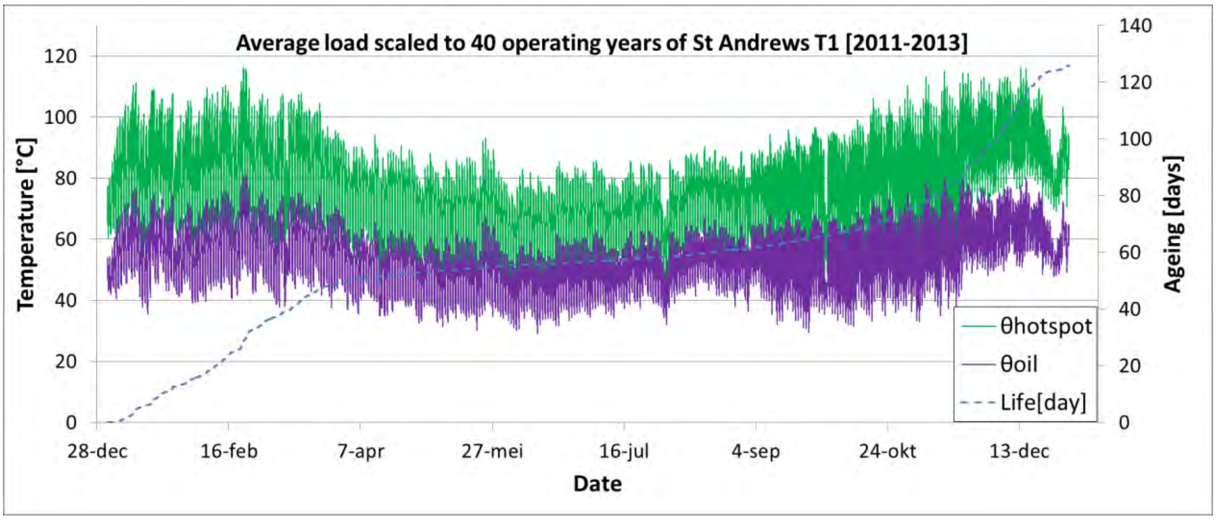


Figure 6-2: Temperature profiles with a peak loading of 28,1 MVA to reach a maximum lifetime of 40 years

To reach an expected life of 60 years, the transformer load can be increased peaking at 481 A or 27,5 MVA. Under these operating conditions, the maximum temperatures are significantly higher than the values given in the IEC 60076-2, see Figure 6-3. However, the maximum temperatures are lower than the values given in the IEC 60076-7 as limits applicable to loading beyond nameplate rating.

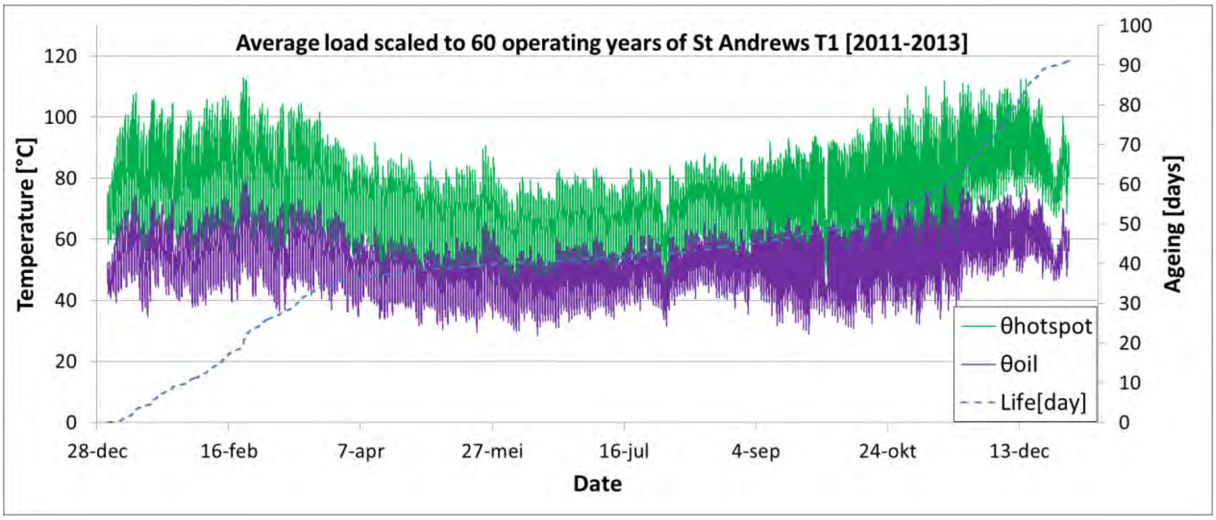


Figure 6-3: Temperature profiles with a peak loading of 27,5 MVA to reach a maximum lifetime of 60 years

Above presented results are summarized in Table 6-2.

Table 6-2: Maximum top oil, winding and hotspot temperature at load profiles peaking at a load leading to an expected lifetime of 15, 40 and 60 years

Load relative to current load profile	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**≤105**	**≤120**	**≤140**
15 years – 531 A	89	119	129
40 years – 493 A	81	108	116
60 years – 481 A	79	105	113

6.2 Summary nominal ageing assuming no moisture

In a similar way, the maximum top oil, winding and hotspot temperature has been estimated for the other transformers. The results are summarized in the following tables.

As was already discussed in the example of St. Andrews T1, Table 6-3 shows similar results for the other transformers. Depending on the present load profile artificially increased to a peak at rated load, the uplift could be between 40 and 55% to reach an expected lifetime of 15 years. The transformers at Cupar, Ruabon and Whitchurch are on or over the maximum uplift limit of 50% as given in the IEC 60076-7, which is in agreement with the temperature limits given in the same standard (140°C hotspot temperature). Thus for these four transformers, the rating uplift is limited by the maximum current increase of 50%.

Table 6-3: Maximum current, ratio maximum and rated current, top oil, winding and hotspot temperature at load profiles peaking at a load leading to an expected lifetime of 15 years

Load relative to current load profile	Peak current (rated current) [A]	Peak current/ Rated current	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**n/a**	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**n/a**	**≤1,5**	**≤105**	**≤120**	**≤140**
St. Andrews T1	531 (367,5)	1,44	89	119	129
St. Andrews T2	514 (367,5)	1,40	91	121	130
Cupar T1	556 (367,5)	1,51	96	131	142
Cupar T2	556 (367,5)	1,51	96	131	142
Ruabon T1	272 (175,0)	1,55	96	131	142
Whitchurch T1	263 (175,0)	1,50	97	130	140
Yockingsgate T1	191 (131,3)	1,45	92	122	131
Liverpoolroad T1	185 (131,3)	1,41	91	123	132

To reach an expected lifetime of at least about 40 years, the load can be increased up to 30-45%, see Table 6-4. Under these operating conditions the hotspot temperature approaches the limit of 140 °C.

Table 6-4: Maximum current, ratio maximum and rated current, top oil, winding and hotspot temperature at load profiles peaking at a load leading to an expected lifetime of 40 years

Load relative to current load profile	Peak current [A]	Peak current/ Rated current	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**n/a**	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**n/a**	**≤1,5**	**≤105**	**≤120**	**≤140**
St. Andrews T1	493 (367,5)	1,34	81	108	116
St. Andrews T2	479 (367,5)	1,30	84	110	119
Cupar T1	520 (367,5)	1,42	88	120	130
Cupar T2	520 (367,5)	1,42	88	120	130
Ruabon T1	254 (175,0)	1,45	87	120	130
Whitchurch T1	245 (175,0)	1,40	89	119	128
Yockingsgate T1	177 (131,3)	1,35	84	112	120
Liverpoolroad T1	172 (131,3)	1,31	84	112	121

To reach an expected lifetime of at least about 60 years, the load can be increased up to 26-41%, see Table 6-5.

Table 6-5: Maximum current, ratio maximum and rated current, top oil, winding and hotspot temperature at load profiles peaking at a load leading to an expected lifetime of 60 years

Load relative to current load profile	Peak current [A]	Peak current/ Rated current	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**n/a**	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**n/a**	**≤1,5**	**≤105**	**≤120**	**≤140**
St. Andrews T1	481 (367,5)	1,31	79	105	113
St. Andrews T2	464 (367,5)	1,26	81	106	114
Cupar T1	506 (367,5)	1,38	85	116	125
Cupar T2	506 (367,5)	1,38	85	116	125
Ruabon T1	247 (175,0)	1,41	84	115	125
Whitchurch T1	238 (175,0)	1,36	86	115	124
Yockingsgate T1	171 (131,3)	1,30	81	107	115
Liverpoolroad T1	167 (131,3)	1,27	81	108	117

6.3 Summary nominal ageing assuming 2% moisture

As mentioned, the condition assessment report /5/ showed that some moisture was present in the oil of the transformers. Although the levels are very low, in /4/ it was shown that moisture levels of 2% have been measured in transformers. Such moisture content would significantly increase the ageing rate of the insulation paper. Instead of having a lifetime of 15 years, this could reduce to 0.8 years. So assuming presence of 2% moisture content, this means that the ageing rate to reach an expected lifetime of 40 years is 7.3 days / year.

Despite the fact that the actual moisture content in the transformers is significantly smaller than this 2%, simulations have been performed assuming 2% moisture content. From the simulations, the peak current of the actual load-profiles for the different transformers to reach a minimum lifetime of 40 years with 2% moisture content is summarized in Table 6-6. It shows that even in the case of 2% moisture, the current can still peak at the rated current and even 2-15% higher peak levels can be allowed. However, under these worst-case assumptions, it is clear that not for all transformers an uplift of 8-12% is possible.

Table 6-6: Maximum current, ratio maximum and rated current, top oil, winding and hotspot temperature at load profiles peaking at a load leading to an expected lifetime of 40 years with 2% moisture content

Load relative to current load profile	Peak current (rated current) [A]	Peak current/ Rated current	Top oil temperature [°C]	Winding temperature [°C]	Hotspot temperature [°C]
IEC 60076-2 (nominal loading)	**n/a**	**n/a**	**n/a**	**≤85**	**≤98**
IEC 60076-7 (higher loading)	**n/a**	**≤1,5**	**≤105**	**≤120**	**≤140**
St. Andrews T1	388 (367,5)	1,06	62	81	87
St. Andrews T2	374 (367,5)	1,02	65	83	88
Cupar T1	412 (367,5)	1,12	66	90	97
Cupar T2	412 (367,5)	1,12	66	90	97
Ruabon T1	202 (175,0)	1,15	66	88	95
Whitchurch T1	191 (175,0)	1,09	66	88	95
Yockingsgate T1	135 (131,3)	1,03	65	83	89
Liverpoolroad T1	133 (131,3)	1,02	64	84	90

6.4 Conclusions

Based on the investigations performed in this section it can be concluded that the transformers can be significantly higher peak-loaded. In several cases, the peak-current exceeds the limit provided by the IEC 60076-7 of 1.5 I_{rated}. In almost all studied situations, the hotspot temperature exceeds or approaches the 140 °C which is a practical limit given in the IEC for emergency loading. Unfortunately the duration such increased temperature is not given by the IEC. As discussed in /10/, the following guidelines for duration are given:

- Long-time Emergency Loading: In situations where a transformer is expected to carry emergency loads, the hot-spot temperature can rise to 140° C. This is not a normal operating condition and is expected to cover a prolonged outage (from several hours to several months) to some system element (single contingency outage). Expectation is that these types of events will occur only two or three times over the life of the transformer.
- Short-time Emergency Loading: For highly unlikely conditions (second and third contingencies) the hot-spot temperature can be allowed to go as high as 180° C. This would be expected to occur for a short period (two to three hours) and only once or twice over the life of the transformer.

In case 2% moisture content it was concluded that not for all transformers an uplift of 8-12% is possible.

7 SENSITIVITY ANALYSIS

The simulations performed in this study have been performed according to typical values recommended by the IEC 60076-7 standard. To investigate the impact of several recommended constants a sensitivity analysis has been performed. Also the impact of increase in rating above nameplate rating on the maximum temperatures and ageing rates has been studied. The results of the different sensitivity analysis have been described in the following sections.

7.1 Hot spot factor

It is known that the hot spot factor is not a constant value, but differs for different transformers /9/. Figure 7-1 shows a probability distribution plot showing that the hot spot factor can vary between 0,5 and 2,1, with an average value of 1,3 which has become the recommended value in IEC. Typical values are between 0,9 and 1,6.

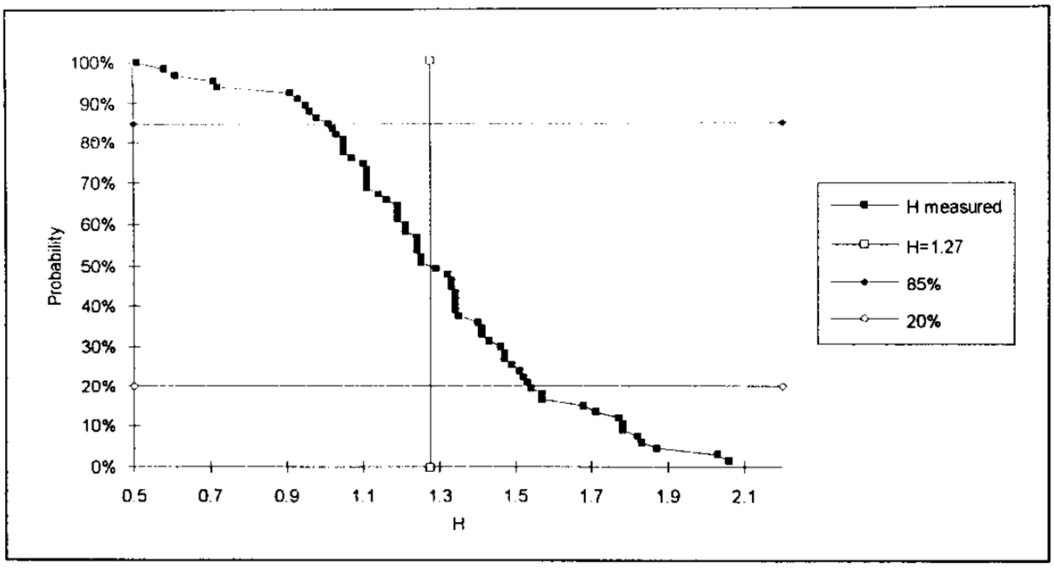


Figure 7-1: Probability distribution of hot spot factor /9/.

The hot spot factor has been varied between 0,5 and 2,1 to study the impact on the hot spot temperature. The result is shown in Figure 7-2. It shows a significant change of the hot spot temperature with a change of the hot spot factor. The change is approximately 2 °C per 0,1 change in the hot spot factor. Considering the range with highest probability between 0,9 and 1,6, thus means that the hot spot temperature can either be 8 °C lower or 6 °C higher compared to the theoretical value.

Therefore it can be concluded that the hot spot factor has a significant impact on the simulation results and a temperature rise test is recommended to estimate the hot spot factor.

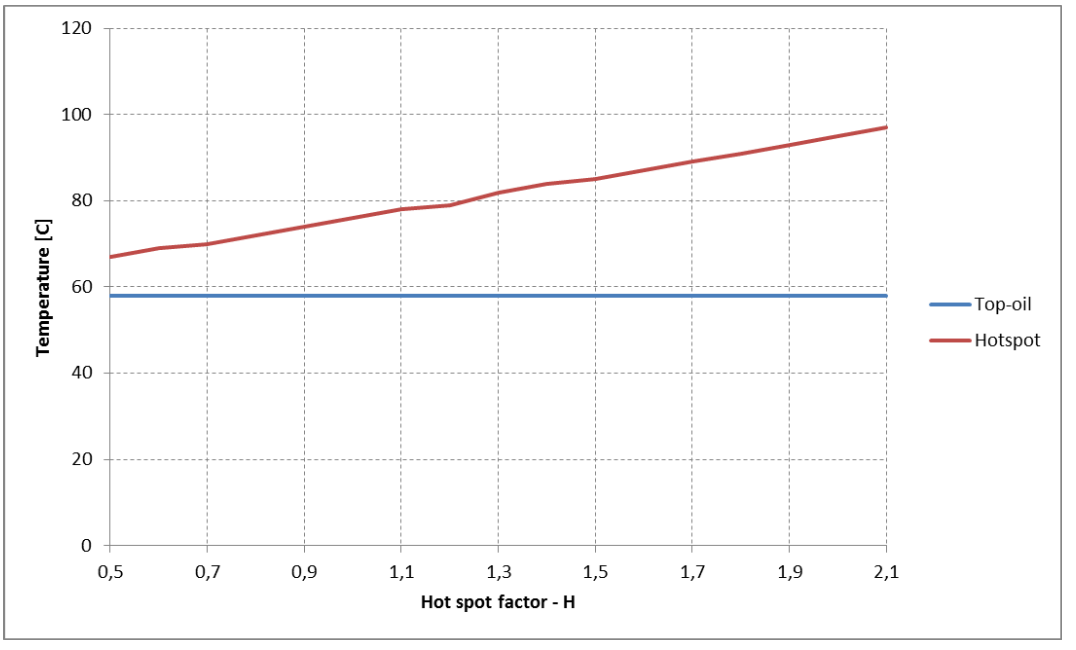


Figure 7-2: Top oil temperature and hot spot temperature as function of the hot spot factor

7.2 Ratio of load losses at rated current to no-load losses

A second parameter that can vary between different transformers is the ratio of the load losses at rated current to no-load losses. To assess the influence of this ratio on the assessment of temperatures, it has been varied from 4 to 8. The result of this assessment is shown in Figure 7-3 and it is clear that this ratio has no significant influence on the maximum temperatures of the transformer.

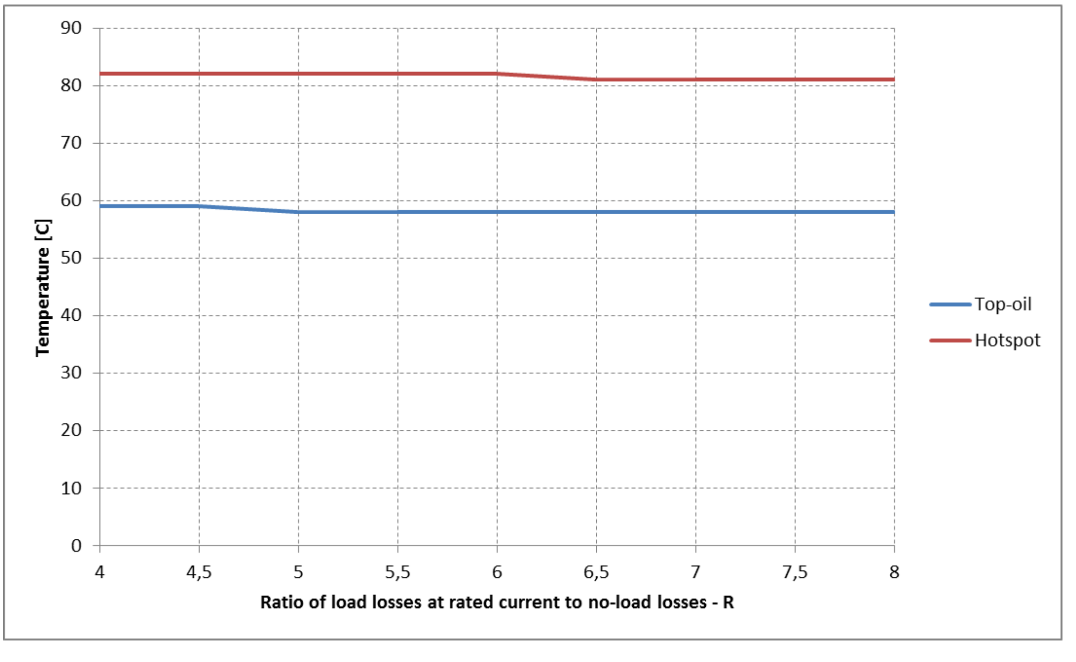


Figure 7-3: Top oil temperature and hot spot temperature as function of the ratio of load losses at rated current to no-load losses

7.3 Ageing rate for loading above nameplate rating

It became clear in the previous chapters that the ageing rate increases rapidly when the loading exceeds the nameplate rating. The relation between loading above nameplate rating and lifetime reduction per year is shown in Figure 7-4. As soon as the peak load is increased 20% above name plate rating, the life time reduction per % load increase, increases significantly. For example, the difference between 20% and 21 % gives 3 days of life time reduction, whereas the difference between 30% and 31 % already results in 9 days additional life time reduction per year and between 40% and 41% the additional life time reduction is 25 days per year.

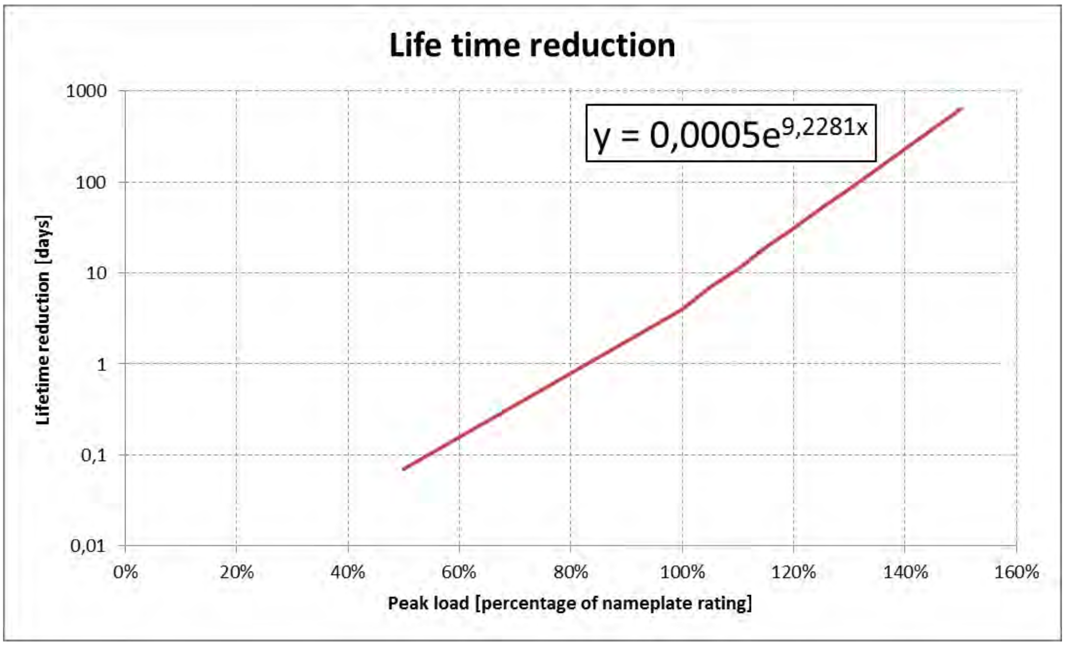


Figure 7-4: Life time reduction as function of the peak load

Due to the linear relation between the peak load and the hot spot temperature, a similar relation between the hot spot temperature and the life time reduction can be concluded, see Figure 7-5.

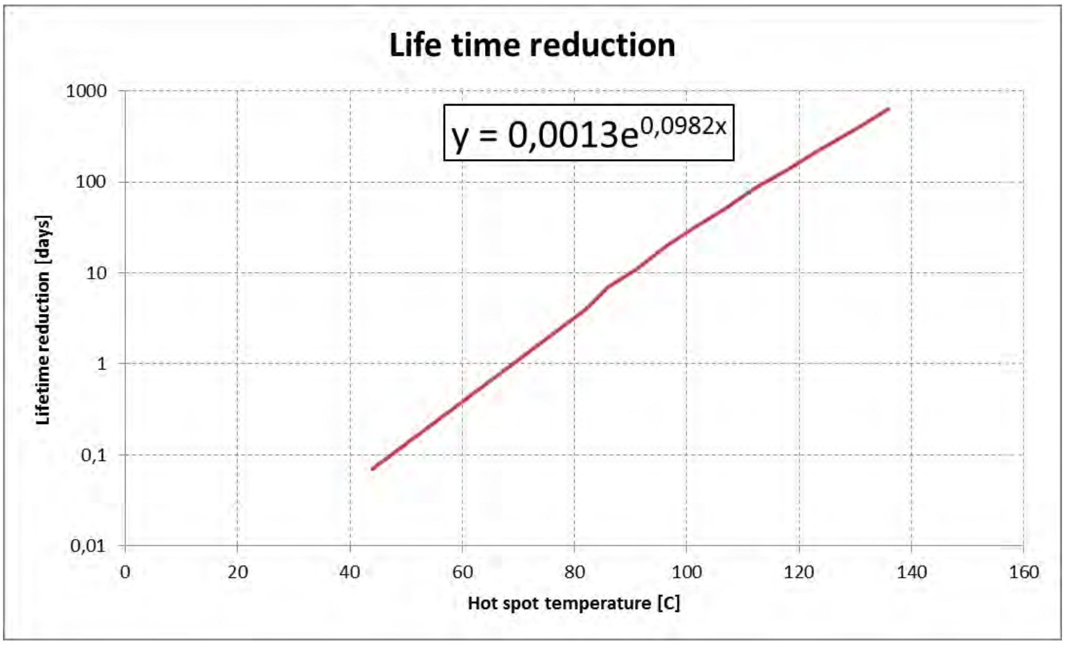


Figure 7-5: Life time reduction as function of the hot spot temperature

Some typical values are shown in Table 7-1. Especially at temperatures above 120 °C the additional life time reduction per °C increases rapidly. So a small difference in the actual value of the hot spot factor compared to the internationally agreed value of 1,3 in the standard which has been used in this report can lead to significantly different ageing rates at temperatures above 120 °C. In particular, if the hot spot factor is 1,6 instead of the used 1,3, the hot spot temperature is 6 °C higher than the calculated value, resulting in significant more ageing than would be estimated by the model.

Table 7-1: Examples of the effect of 1 °C temperature rise on the life time reduction

From	To	Life time reduction per 1 °C
100 °C	101 °C	+ 3 days
110 °C	111 °C	+ 7 days
120 °C	121 °C	+ 18 days
130 °C	131 °C	+ 40 days
140 °C	141 °C	+ 89 days

7.4 Conclusions

From the sensitivity analysis of different parameters in the model, it can be conclude that:

1. The calculated hot spot temperatures are highly dependent on the hot spot factor and can result in a difference in the hot spot temperature from -8 °C to +6 °C
2. The calculated hot spot temperatures are not significantly influenced by the ratio of load losses at rated current to no-load losses
3. The life time reduction increases significantly for hot spot temperatures above 120 °C and considering the possible impact of the hot spot factor on the hot spot temperature, it could be advised to limit the hot spot temperature

8 FUTURE LOADS

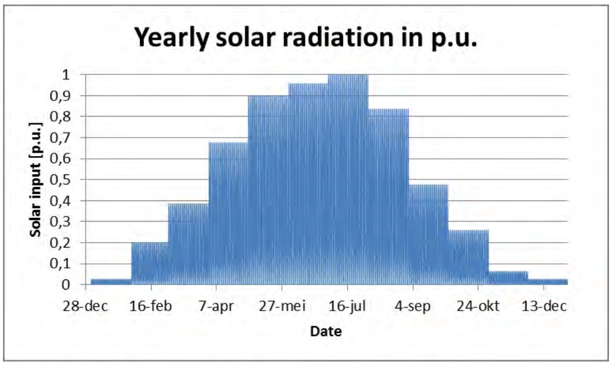
As mentioned in the introduction, connections to low carbon technologies like wind and solar as well as heat pumps and charging of electrical vehicles are expected to increase in the future. As a result, the loading of the grid will change, both as load increase and as more dynamic behavior. Therefore, SPEN is seeking ways to utilize the flexibility in their networks in order to increase and enhance the transport capability.

As discussed, the investigated power transformers can be loaded higher if the dynamic behavior of the load and the ambient temperature is taking into account. This is however based on the actual loading pattern.

Looking to future loading patterns, the impact of solar energy generation, charging of electrical vehicles and the use of electric heating on the loading of the power transformers will be further discussed in the following sections. Due to confidentiality, the sources behind the profiles cannot be disclosed.

8.1.1 Solar power

SPEN expects an increase in the integration of solar energy. Typical solar radiation patterns are shown in Figure 8-1. As expected, it shows that the highest generated solar power can be expected between late spring and early autumn as well that the highest peak occurs around noon.



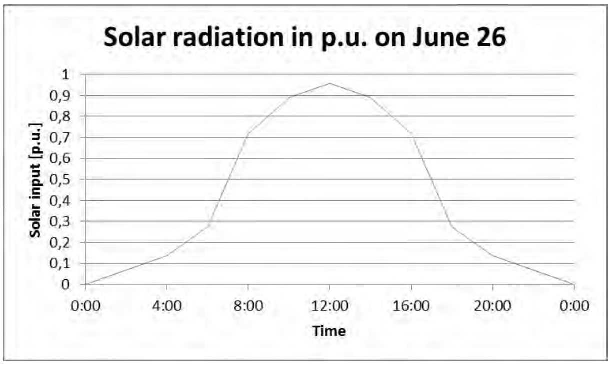
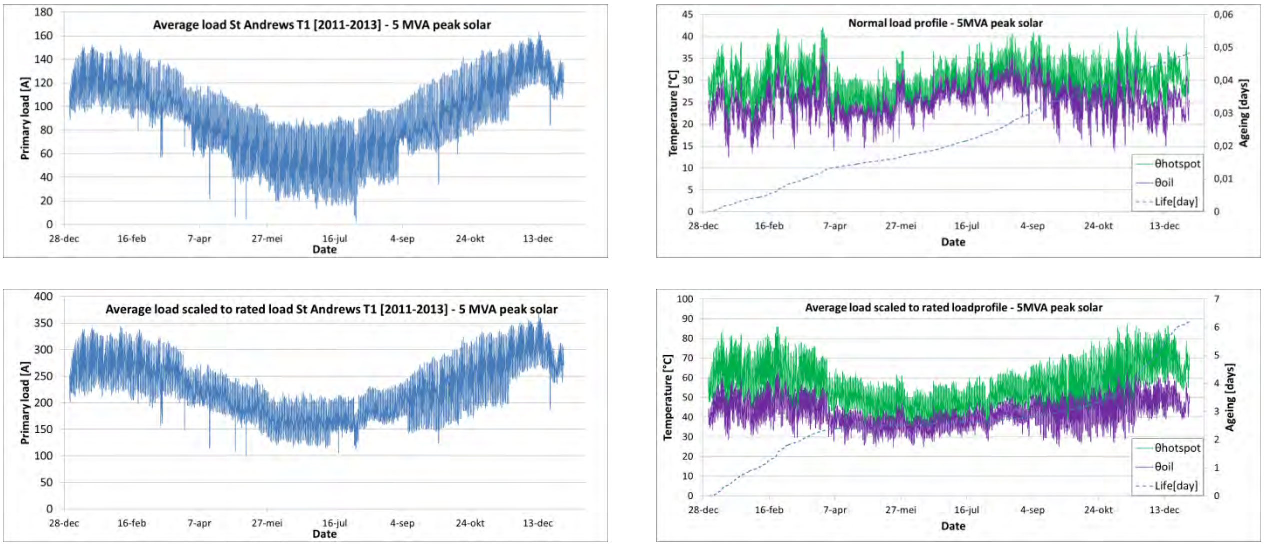


Figure 8-1: Examples of typical solar radiation patterns per year (left) and on June 26 (right)

The impact of additional load increase of the transformers due to solar power generation has been determined for transformer T1 at substation St. Andrews. A maximum power of 5 MVA is foreseen by SPEN. As the solar energy is planned to be installed locally, this will reduce the power flow through the transformer.

The additional 5 MVA of solar power has been subtracted from the actual load profile and the load profile peaking at nameplate rating. The resulting load profiles and temperature profiles are shown in the figures below.



The main results from the analysis performed in this section are summarized in Table 8-1.

Table 8-1 Hot spot temperature and ageing for different solar peak loadings

	Hot spot [°C]	Ageing [minutes/year]
Actual load profile	45	107
- 5 MVA solar	42	70
21 MVA load profile	88	13.022
- 5 MVA solar	87	8.933

From Table 8-1 can be concluded that 5 MVA peak power generated by solar energy thermally reliefs the transformer.

8.1.2 Electrical heating

SPEN expects an increase in the integration of electrical heating. A typical year pattern is shown in Figure 8-2. As expected, it shows that the highest load is expected between early autumn and late spring.

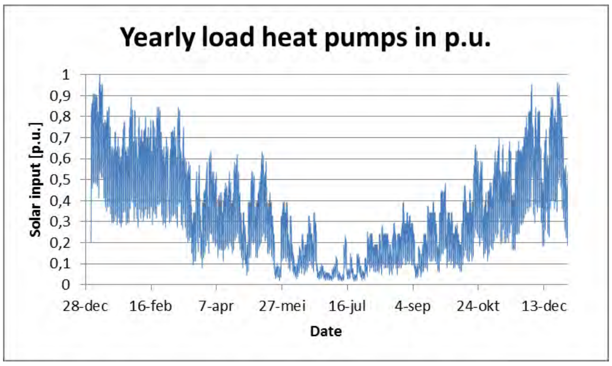
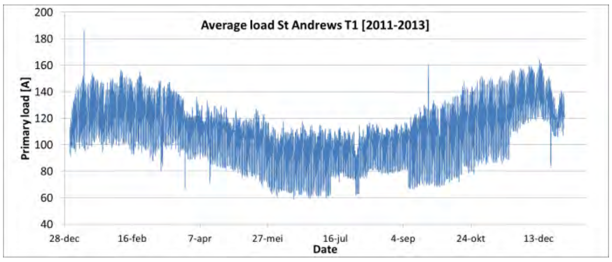
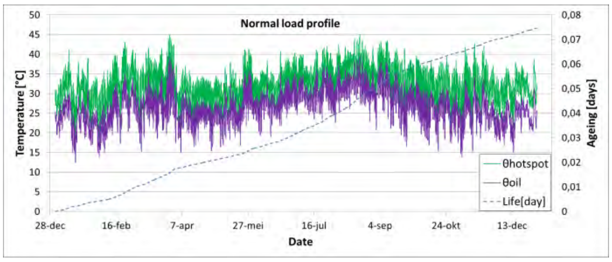
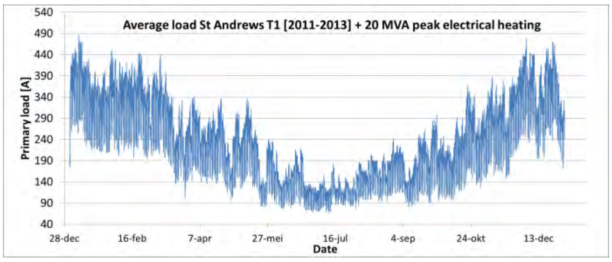


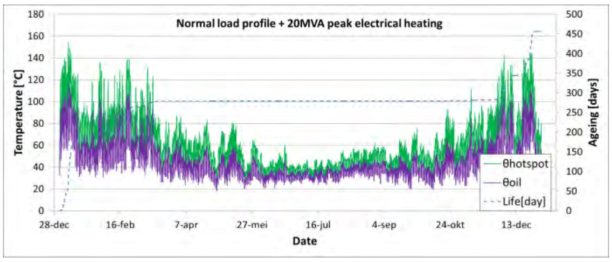
Figure 8-2: Example of typical electrical heating patterns per year

The impact of additional load increase of the transformers due to the installation of electrical heating has been determined for transformer T1 at substation St. Andrews. First, the additional load of electrical heating has been superimposed on the actual load profiles, with a peak power of 5, 7,5, 15 and 20 MVA. Below the simulation results for the actual load profile and the 20 MVA profile are shown.

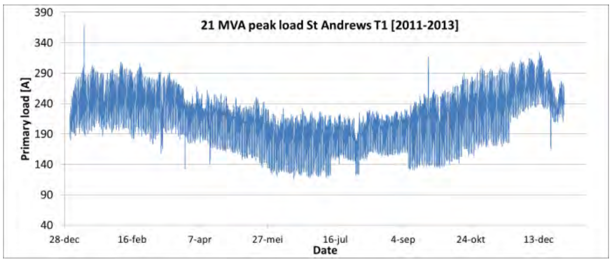


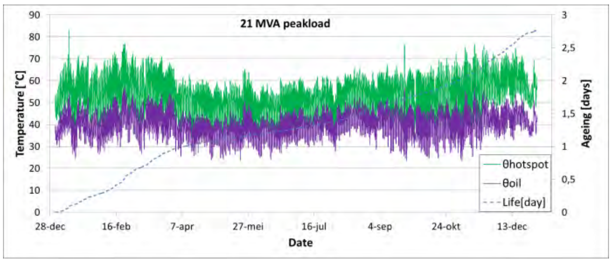


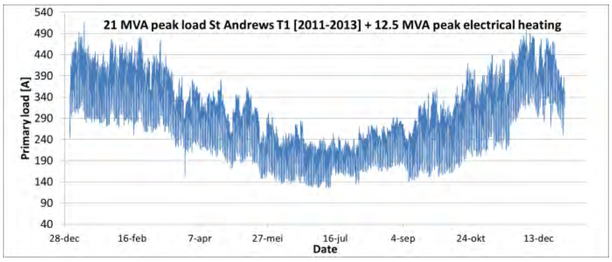


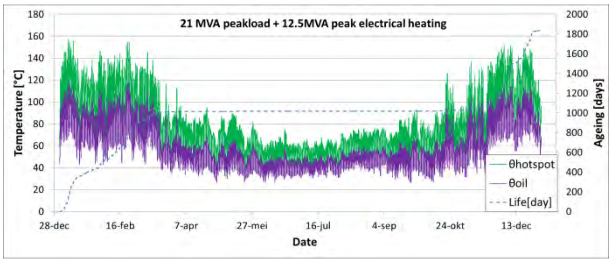


Secondly, additional heat pump peak power of 7.5, 10 and 12.5 MVA has been superimposed on the loadprofile which has already been artificially increased to a peak power of 21 MVA. Below the simulation results for the 21 MVA loadprofile and the 12.5 MVA profile are shown.









The main results from the analysis performed in this section are summarized in Table 8-2.

Table 8-2 Hot spot temperature and ageing for different heating peak loadings

	Hot spot [°C]	Ageing [days/year]
Actual load profile	45	0,1
+ 7.5 MVA heating	66	0,4
+ 15 MVA heating	115	10
+ 20 MVA heating	154	456
21 MVA load profile	83	3
+5 MVA heating	112	16
+7.5 MVA heating	131	102
+10 MVA heating	143	499
+12.5 MVA heating	157	1836

From above table can be concluded that 15 MVA peak power required to use electric heating can be distributed by the transformer without significant ageing. In case the actual load pattern is increased to a rated peak value of 21 MVA, then still 5 MVA of additional peak power to supply electric heating could be transported by the transformer without significant ageing.

8.1.3 Electrical vehicle

SPEN expects an increase in the integration of electric vehicles for the decarbonisation of transport. Typical patterns are shown in Figure 8-3.

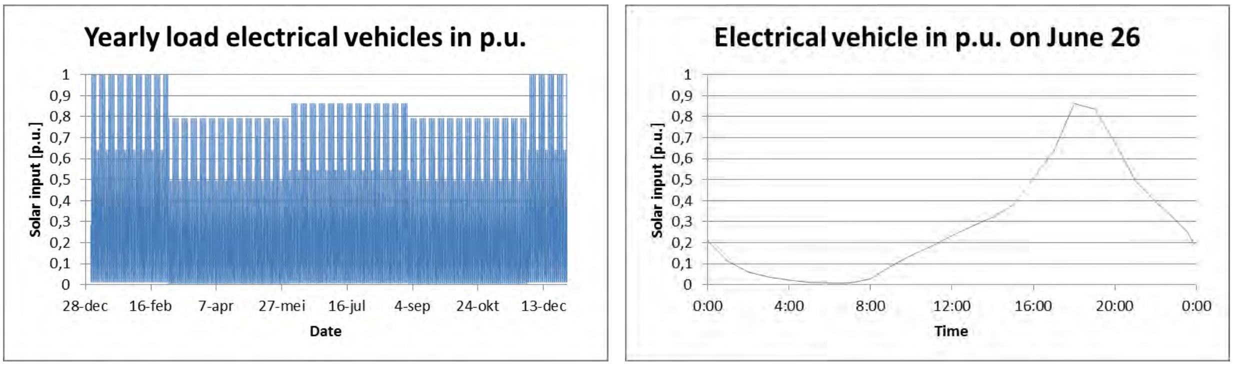
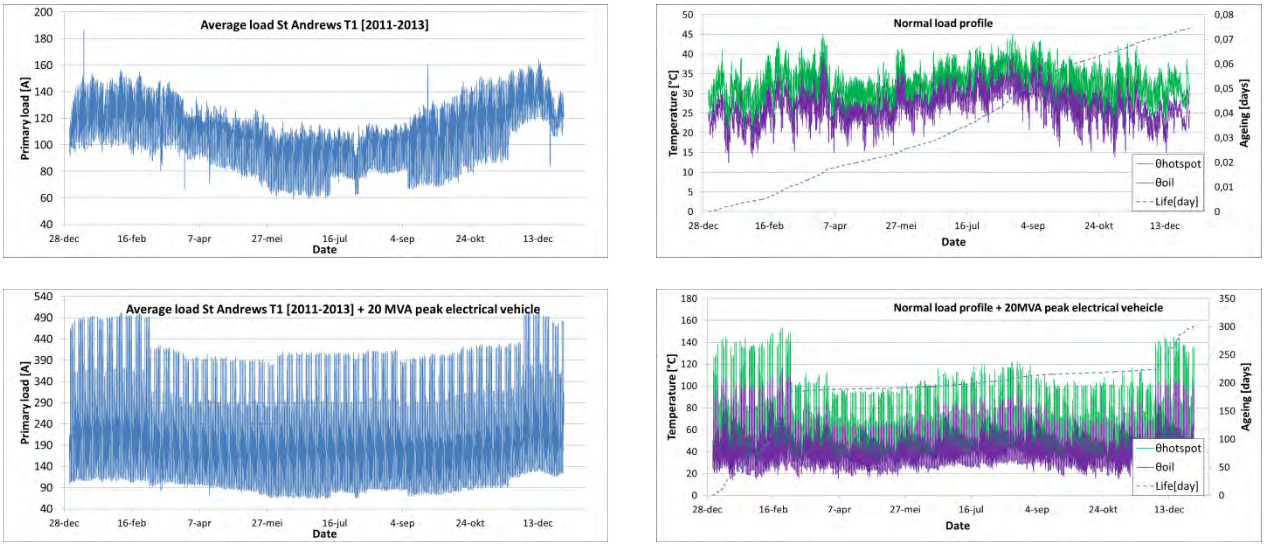
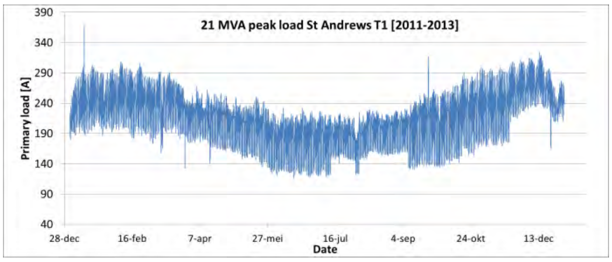


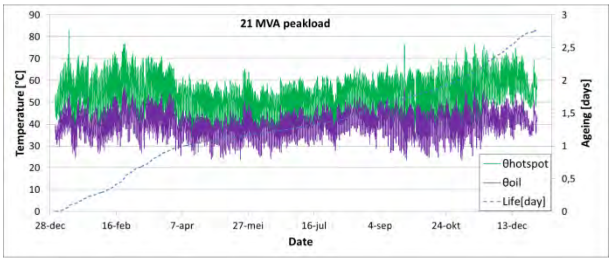
Figure 8-3: Examples of load patterns of electrical vehicles per year (left) and on June 26 (right)

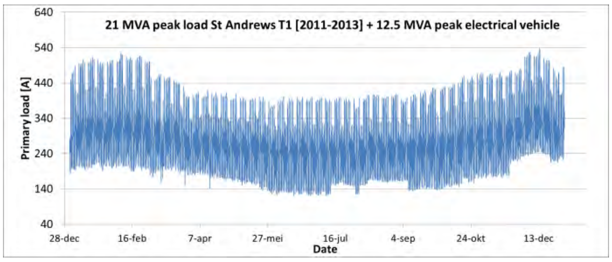
The impact of additional load increase of the transformers due to charging of electrical vehicles has been determined for transformer T1 at substation St. Andrews. First, the additional load has been superimposed on the actual load profiles, with a peak load of 7.5, 15 and 20 MVA. Below the simulation results for the actual load profile and the 20 MVA profile are shown.

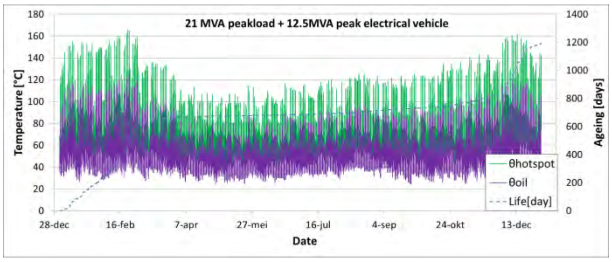


Secondly, additional loading due to charging of electrical vehicles of 5, 7,5, 10 and 12,5 MVA has been superimposed on the load profile which has already been artificially increased to a peak power of 21 MVA. Below the simulation results for the 21 MVA load profile and the 12,5 MVA profile are shown.









The main results from the analysis performed in this section are summarized in Table 8-3.

Table 8-3 Hot spot temperature and ageing for different loadings due to electrical vehicles

	Hot spot [°C]	Ageing [days/year]
Actual load profile	45	0,1
+ 7.5 MVA vehicles	70	0,4
+ 15 MVA vehicles	112	10
+ 20 MVA vehicles	153	303
21 MVA load profile	83	3
+5 MVA vehicles	106	12
+7.5 MVA vehicles	128	44
+10 MVA vehicles	147	243
+12.5 MVA vehicles	166	1194

From above table can be concluded that 15 MVA peak power required to charge electric vehicles can be supplied by the transformer without significant ageing. In case the actual load pattern is increased to a rated peak value of 21 MVA, then still 5 MVA of additional peak power to charge electric vehicles could be transported by the transformer without significant ageing.

9 TRANSFORMER LOADING CAPABILITIES

Based on the simulations presented in the previous chapters, it can be concluded that the transformers are currently operated well within their thermal capability. This is due to the fact that the present peak load is only 40-68% of the nameplate rating. The simulated internal temperatures are well below the recommended limits of IEC 60076-2 and 60076-7. It can be concluded that room is available to investigate further increase of the transformer load, using the typical given load-profile, typically to reach at least the nameplate rating and if possible above.

During contingency the load of the transformers can temporary (minutes to months) double and the peak value can reach the nameplate rating or above. It was shown by simulations using a load profile with a peak at rated power still the maximum temperatures stay within the limits recommended by IEC. Moreover, the lifetime reduction is only a couple of days per year. A further increase of the load profile by 8% results in hot spot temperatures below 98°C. Additional increasing the load by 10% and 12% results in maximum temperatures exceeding the continuous loading temperatures as provided by IEC. Still the temperatures fall within the limits for temporary higher loading (emergency loading), which is applicable in case of contingency situations. As a consequence higher than nominal ageing occurs during small periods of time but lifetime reduction over one year is still not very significant. It can be concluded that in case of contingency, the transformers can be loaded 12% above nameplate rating (peak rating), considering the present load profile.

To reach an expected lifetime of at least about 40 years it was concluded that the load can be increased by another 30-45% on top of the load profile peaking at rated power. Under these operating conditions the hotspot temperature approaches the limit of 140 °C. In case 2% moisture content is present inside the paper insulation it was concluded that an uplift of 8-12% is not possible for all transformers if an expected lifetime of at least 40 years is required.

Because the simulations performed are based on theory only, a brief sensitivity analysis of different parameters in the model has been performed. It was shown that the calculated hot spot temperatures are highly dependent on the hot spot factor and can result in a significant difference in the hot spot temperature from -8 °C to +6 °C. The calculated hot spot temperatures are not influenced by the ratio of load losses at rated current to no-load losses. The life time reduction increases significantly for hot spot temperatures above 120 °C and considering the possible impact of the hot spot factor on the hot spot temperature, it could be advised to limit the hot spot temperature.

The main reason to investigate available thermal room in the transformers was to enable the installation of renewable energy generation or future electric loads. From the analysis performed on transformer T1 at substation St. Andrews it was concluded that the presence of 5 MVA solar energy in a residential area would relief the thermal stress of the transformers by several degrees centigrade. Moreover, on top of the current load profile, up to 15 MVA of additional peak loading from electrical vehicles or heating can be supported by St. Andrews T1.
In case the current load profile reaches a peak loading of transformer rating (21 MVA), still around 5 MVA of additional peak load can be allowed.

10 RTTR ADDED VALUE, EFFECTIVENESS AND LIMITATIONS

Currently all eight investigated transformers are thermally low loaded, with a rather constant temperature profile. With respect to the current load profile, the sought 12% increase in transformer loading can be well achieved without thermally stressing the transformers to the limits.

In case the actual load profile increases to a peak loading of the rating of the transformer, an additional increase by 12% is possible but in that case the hot-spot temperature temporarily exceeds 98 °C which means temporarily accelerated ageing. Still the peak loading of the transformers can be increased even further up to 50%, depending on the current load profile, the present moisture content and the expected technical lifetime.

Besides increasing the load profile with a certain percentage, the impact of implementing renewable energy (in this case solar power was studied), electrical heating and charging of electrical vehicles is of interest to SPEN. It was shown that on top of the current load profile, up to 15 MVA of additional peak loading can be allowed.

Finally it was concluded that when the transformers are operating close to the thermal limit, the ageing rate of the transformer increases rapidly and thus care should be taken when operating close to the thermal limit. In particular the impact of the unknown real hot spot factor can significantly impact the hot spot temperature. If no heat-run test results are available, a dynamic thermal rating system may be of interest to keep firm control over the situations. This will be discussed in more detail in the next sections.

10.1 Added value

As mentioned, if the distribution transformers are going to be run closer to the design limitations, a monitoring system predicting the room for extra loading without jeopardizing the transformers reliability and availability may be of interest to keep firm control over the situation.

By making use of dynamic rating, the power transformer loading capabilities can be determined accurately. As was shown by the desktop study, due to the actual load profile and ambient temperature profile, the loading may be increased significantly for various transformers. This means that the distribution capabilities of the SPEN network can be increased without having to invest in new equipment. However, this needs careful monitoring and needs to be reconsidered continuously to ensure that the transformer is not exceeding the limits. Due to the rather fast response of a transformer to load changes, and the difficult-to-predict nature of load variations over time in future, monitoring in combination with predictive modelling is helpful. Besides safe increase of the continuous rating of the transformers, RTTR facilitates controlled emergency loading beyond nameplate rating without unjustified risk. In particular, instead of flying blind, RTTR provides timely and accurate information as to the real thermal limit at any moment in real time.

RTTR supports more efficient asset's utilisation because the component can operate at a temperature close to but within design limits which will approach nominal ageing rate.

Because the transformers will be monitored and assessed continuously using RTTR, there will be no increase of the present risk in the network, as hot-spots will be detected or can be predicted. As a consequence, SPEN can profit from a more cost-effective and less constrained network with similar availability. Furthermore, with continuous assessments with a dynamic rating system in place, also full transparency can be created in the decision making process to load transformers higher than usual. The dynamic rating system provides all historic loading and future loading possibilities, including its thermal consequences, which are needed to do so.

10.1.1 Engineering point of view

From an engineering point of view, the following three major advantages for implementing real-time thermal rating can be distinct.

First of all, the engineer will improve its knowledge as RTTR is based on actual measured temperatures. With this knowledge and verified thermal models inside the RTTR system, measurements on individual transformers can be extrapolated to groups of similar transformers under similar operating conditions. It thus enables early warnings when certain set limits are reached or will be reached. This knowledge enhances confidence in the network operation and supports timely actions like load-shedding. The thermal ageing of the transformer is stored and monitored resulting in an improved insight in the utilisation of the transformer.

Secondly, RTTR on power transformers allows for a safe increase of loading and temporary higher loading in case of integration of renewable energy, electric heating, electric cars, etc. which is expected in the near and far future, or simply in an emergency situation. As a result, the grid operators are supported to make well-considered decisions to curtail the connected wind turbines or other generation sources. Moreover, intraday and day-ahead forecasts helps in managing congestion issues in a more efficient way and most likely reduces the number of necessary actions to be taken such as dispatching or starting emergency generation.

Thirdly, the actual and predicted data will be stored leading to an improved thermal model of the transformer, knowledge about possible loading capabilities of transformers which can be used as input for short and long-term plans for the management of the SPEN network.

10.2 Effectiveness and accuracy

Accuracy

The effectiveness of the RTTR system strongly depends on the accuracy of the inputs feeding the model and the model itself. As was shown, the ambient temperature has a significant impact on the rating of the transformer and needs careful consideration when looking for working at or near the limits of the transformer dynamic rating.

Therefore, accurate measurement of ambient and transformer top oil temperature in combination with the prediction capabilities of a dynamic rating system will support the utility to keep the transformer operating safely within the allowed temperature range.

Effectiveness

Though a single dynamic rating system on a single transformer is shown to be quite interesting from a technical and business viewpoint already, another solution is also possible. In this alternative solution, a single dynamic rating system is used to represent a group of rather similar transformers in the SPEN network. Then, probably with a limited amount of dynamic rating systems, SPEN could model the majority of the MV transformers in the complete network.

In this case, the effectiveness of the RTTR system itself is somewhat reduced because of a difference between an individual transformer and the group of transformers it belongs to. However, it is believed that the effectiveness remains high enough to ensure an interesting increased loading compared to the nameplate rating.

Typically, DNV GL standard software for dynamic rating systems for transmission assets can accommodate up to 5 different models for power transformers simultaneously. It is believed that by using two or three full software systems (10-15 transformer models), a majority of the transformer fleet of SPEN could be modelled.

10.3 Conclusions

Due to the load pattern, the peak loading of the transformer can easily exceed the name plate rating by the sought 12% without resulting in higher than nominal loss of life. To ensure the loss of life remains close to but below the nominal value, monitoring and real-time thermal rating should be considered. As a result, the transformers will be better utilised in a fully transparent way, without decrease in reliability or availability and investments in new and larger transformers can be extended.

From an efficiency and cost-reduction point-of-view, groups of similar transformers can be defined e.g. based on rating, manufacturer, age, location, etc. To accommodate thermal rating on such group only one thermal model is required reducing cost for software development and hardware. Investments cost can be divided over several transformers within each group.

11 CONCLUSIONS AND RECOMMENDATIONS

From the analysis presented in this report, the following conclusions can be drawn:

1. All transformers are currently thermally low loaded
2. The temperature of the transformers is rather constant. This is due to the fact that the loading is highest in the winter when the ambient temperature is lowest and vice versa in the summer
3. Peak loadings can be increased above nameplate rating by 30-45% ensuring an expected technical lifetime of 40 years, given the situation in the current evaluation period and the parameters used in the model are sufficiently representative for the different transformers
4. With respect to integrating future loads coming from solar energy, electrical heating, electrical vehicles, etc., up to 15 MVA of additional peak loading can be allowed on top of the current load profiles
5. Close to the thermal limit, the ageing rate of the transformer increases rapidly and thus care should be taken when operating close to the thermal limit. The life time reduction increases significantly for hot spot temperatures above 120 °C and considering the possible impact of the hot spot factor on the hot spot temperature, it could be advised to limit the hot spot temperature. To prevent excessive ageing, RTTR is a very suitable means to provide support in the transformer loading so instead of flying blind, RTTR provides timely and accurate information as to the real thermal limit at any moment in real time
6. Using RTTR, full transparency regarding the decision to increase the loading can be provided to regulators and auditors
7. RTTR enhances confidence in the network operation and supports timely actions like load-shedding
8. Knowledge about possible loading capabilities of transformers, gathered with an RTTR system, can be used as input for short and long-term plans for the management of the SPEN network
9. Implementing RTTR results in significant higher profits if compared to the necessary implementation costs and additional costs for losses.

The following recommendations are given:

1. Due to the cyclic load pattern, the peak loading of the transformer can easily exceed the name plate rating without resulting in higher than nominal loss of life. To ensure the loss of life remains close to but below the nominal value, it is recommended to install a monitoring and real-time thermal rating system. Moreover, it is advised to take extra oil-samples during the verification tests after implementing RTTR to ensure no load-related internal defects become active.
2. From an efficiency and cost-reduction point-of-view, groups of similar transformers can be defined e.g. based on rating, manufacturer, age, location, etc. To accommodate thermal rating on such group only one thermal model is required reducing cost for software development and hardware. Investments cost can be divided over several transformers within each group.
3. It is recommended to perform a special test or heat run test as has been defined in /6/. Preferably this test needs to be done for each transformer to know its specific hotspots. To reduce costs, it could be decided to perform such a test once for each group of similar transformers, but then the accuracy for each specific transformer is lower.
4. If a heat run test cannot be performed, it is recommended to limit the hot spot temperature to account for possible deviations of the parameters given in the IEC used in the models from the actual values.

12 REFERENCES

/1/ IEC 60076-7, Power transformers – Part 7: Loading guide for oil-immersed power transformers, 2005

/2/ IEC 60076-2, Power transformers – Part 2: Temperature rise for liquid-immersed transformers, 2011

/3/ FN-LNFC1, Transformer real time thermal rating (RTTR), February 2013

/4/ A review of paper aging in power transformers, D.H. Shroff, A.W. Stannett, IEE Proceedings, Vol. 132, Pt. C, No. 6, November 1985

/5/ DNV GL, Real Time Thermal Rating System – Phase I Asset Condition Assessment, 14-2132, July 14, 2014

/6/ Cigré Technical Brochure 393, Thermal performance of Transformers, WG A2.24, October 2009

/7/ Electra 150, Lifetime evaluation of transformers, WG 12.09, October 1993

/8/ Cigré Technical Brochure 227, Life management techniques for Power Transformers, WG A2.18, June 2003

/9/ Electra 161, Experimental determination of Power Transformer hot-spot factor, WG 12.09, 1995

/10/ Loading of Power Transformers: Reducing Costs Without Affecting Reliability, Burns & McDonell.

APPENDIX A
Transformer details used in modelling

The details of the different transformers that have been used in the transformer model have been gathered. This Appendix summarizes these details.

St. Andrews T1

The following important nameplate details have been gathered for the power transformer T1 located at substation St. Andrews.

General	
Supplier	Bruce Peebles
Year of manufacturing	1966
Serial number	43546
Cooling	ONAF/ONAN
Power	
Nominal power (ONAF)	21 MVA
Nominal power (ONAN)	15 MVA
Voltage	
Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV
Current	
Nominal primary current (ONAF)	367.5 A
Nominal primary current (ONAN)	262.5 A
Nominal secondary current (ONAF)	1103 A
Nominal secondary current (ONAN)	788 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

– Nominal values for the current
  - Primary winding I_{ONAN} 262.5 A I_{ONAF} 367.5 A
  - Secondary winding I_{ONAN} 788.0 A I_{ONAF} 1103.0 A

– Nominal values for the power
  - Primary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA
  - Secondary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA

– Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV U_{ONAF} 33 kV
  - Secondary winding U_{ONAN} 11 kV U_{ONAF} 11 kV

– Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6 R_{ONAF} 6
  - Secondary winding R_{ONAN} 6 R_{ONAF} 6

– Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN/ONAF

- Transition temperatures ONAN – ONAF and ONAF – ONAN
  - Transition from ONAN to ONAF $\Theta_{ONAN-ONAF}$ 75 °C
  - Transition from ONAF to ONAN $\Theta_{ONAF-ONAN}$ 50 °C

- Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
  - ONAF mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$

- Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
  - ONAN mode $\tau_{oil} = 210$ min, $\tau_{winding} = 10$ min
  - ONAF mode $\tau_{oil} = 150$ min, $\tau_{winding} = 7$ min

- Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode $x = 0.8$, $y = 1.3$
  - ONAF mode $x = 0.8$, $y = 1.3$

- Sample time for actual values for current and ambient temperature
  - $t_{sample} = 900$ s (15 minutes)

- Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
  - ONAN mode $(H{\cdot}g_r)_{ONAN} = 26$ °C
  - ONAF mode $(H{\cdot}g_r)_{ONAF} = 26$ °C

St. Andrews T2

The following important nameplate details have been gathered for the power transformer T2 located at substation St. Andrews.

General	
Supplier	Bruce Peebles
Year of manufacturing	1966
Serial number	43545
Cooling	ONAF/ONAN
Power	
Nominal primary power (ONAF)	21 MVA
Nominal primary power (ONAN)	15 MVA
Voltage	
Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV
Current	
Nominal primary current (ONAF)	367.5 A
Nominal primary current (ONAN)	262.5 A
Nominal secondary current (ONAF)	1103 A
Nominal secondary current (ONAN)	788 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

- Nominal values for the current
  - Primary winding I_{ONAN} 262.5 A I_{ONAF} 367.5 A

- Secondary winding I_{ONAN} 788.0 A I_{ONAF} 1103.0 A

– Nominal values for the power
  - Primary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA
  - Secondary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA

– Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV U_{ONAF} 33 kV
  - Secondary winding U_{ONAN} 11 kV U_{ONAF} 11 kV

– Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6 R_{ONAF} 6
  - Secondary winding R_{ONAN} 6 R_{ONAF} 6

– Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN/ONAF

– Transition temperatures ONAN – ONAF and ONAF – ONAN
  - Transition from ONAN to ONAF $\Theta_{ONAN\text{-}ONAF}$ 75 °C
  - Transition from ONAF to ONAN $\Theta_{ONAF\text{-}ONAN}$ 50 °C

– Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
  - ONAF mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$

– Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
  - ONAN mode $\tau_{oil} = 210$ min, $\tau_{winding} = 10$ min
  - ONAF mode $\tau_{oil} = 150$ min, $\tau_{winding} = 7$ min

– Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode $x = 0.8$, $y = 1.3$
  - ONAF mode $x = 0.8$, $y = 1.3$

– Sample time for actual values for current and ambient temperature
  - $t_{sample} = 900$ s (15 minutes)

– Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
  - ONAN mode $(H \cdot g_r)_{ONAN} = 26$ °C
  - ONAF mode $(H \cdot g_r)_{ONAF} = 26$ °C

Cupar T1

The following important nameplate details have been gathered for the power transformer T1 located at substation Cupar.

General

Supplier	Denis Ferranti Limited
Year of manufacturing	1966
Serial number	631708
Cooling	ONAF/ONAN

Power

Nominal primary power (ONAF)	21 MVA
Nominal primary power (ONAN)	15 MVA

Voltage

Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV

Current

Nominal primary current (ONAF)	367.5 A
Nominal primary current (ONAN)	262.4 A
Nominal secondary current (ONAF)	1102 A
Nominal secondary current (ONAN)	786 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

- Nominal values for the current
  - Primary winding I_{ONAN} 262.4 A I_{ONAF} 367.5 A
  - Secondary winding I_{ONAN} 786.0 A I_{ONAF} 1102.0 A
- Nominal values for the power
  - Primary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA
  - Secondary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA
- Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV U_{ONAF} 33 kV
  - Secondary winding U_{ONAN} 11 kV U_{ONAF} 11 kV
- Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6 R_{ONAF} 6
  - Secondary winding R_{ONAN} 6 R_{ONAF} 6
- Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN/ONAF
- Transition temperatures ONAN – ONAF and ONAF – ONAN
  - Transition from ONAN to ONAF $\Theta_{ONAN\text{-}ONAF}$ 75 °C
  - Transition from ONAF to ONAN $\Theta_{ONAF\text{-}ONAN}$ 50 °C
- Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
  - ONAF mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
- Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
  - ONAN mode $\tau_{oil} = 210$ min, $\tau_{winding} = 10$ min
  - ONAF mode $\tau_{oil} = 150$ min, $\tau_{winding} = 7$ min
- Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode $x = 0.8$, $y = 1.3$
  - ONAF mode $x = 0.8$, $y = 1.3$
- Sample time for actual values for current and ambient temperature

- t_{sample} = 900 s (15 minutes)

– Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
  - ONAN mode $(H \cdot g_r)_{ONAN}$ = 26 °C
  - ONAF mode $(H \cdot g_r)_{ONAF}$ = 26 °C

Cupar T2

The following important nameplate details have been gathered for the power transformer T2 located at substation Cupar.

General	
Supplier	Denis Ferranti Limited
Year of manufacturing	1966
Serial number	631709
Cooling	ONAF/ONAN
Power	
Nominal primary power (ONAF)	21 MVA
Nominal primary power (ONAN)	15 MVA
Voltage	
Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV
Current	
Nominal primary current (ONAF)	367.5 A
Nominal primary current (ONAN)	262.4 A
Nominal secondary current (ONAF)	1102 A
Nominal secondary current (ONAN)	786 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

– Nominal values for the current
  - Primary winding I_{ONAN} 262.4 A I_{ONAF} 367.5 A
  - Secondary winding I_{ONAN} 786.0 A I_{ONAF} 1102.0 A

– Nominal values for the power
  - Primary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA
  - Secondary winding P_{ONAN} 15 MVA P_{ONAF} 21 MVA

– Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV U_{ONAF} 33 kV
  - Secondary winding U_{ONAN} 11 kV U_{ONAF} 11 kV

– Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6 R_{ONAF} 6
  - Secondary winding R_{ONAN} 6 R_{ONAF} 6

– Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN/ONAF

– Transition temperatures ONAN – ONAF and ONAF – ONAN

- Transition from ONAN to ONAF — $\Theta_{ONAN\text{-}ONAF}$ 75 °C
- Transition from ONAF to ONAN — $\Theta_{ONAF\text{-}ONAN}$ 50 °C

– Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
- ONAN mode — $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
- ONAF mode — $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$

– Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
- ONAN mode — τ_{oil} = 210 min, $\tau_{winding}$ = 10 min
- ONAF mode — τ_{oil} = 150 min, $\tau_{winding}$ = 7 min

– Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
- ONAN mode — $x = 0.8$, $y = 1.3$
- ONAF mode — $x = 0.8$, $y = 1.3$

– Sample time for actual values for current and ambient temperature
- t_{sample} = 900 s (15 minutes)

– Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
- ONAN mode — $(H{\cdot}g_r)_{ONAN}$ = 26 °C
- ONAF mode — $(H{\cdot}g_r)_{ONAF}$ = 26 °C

Ruabon T1

The following important nameplate details have been gathered for the power transformer T1 located at substation Ruabon.

General	
Supplier	ABB Elektrik Sanayi A.S.
Year of manufacturing	2013
Serial number	1LTR0020547
Cooling	ONAF/ONAN
Power	
Nominal primary power (ONAF)	10 MVA
Nominal primary power (ONAN)	7.5 MVA
Voltage	
Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV
Current	
Nominal primary current (ONAF)	175.0 A
Nominal primary current (ONAN)	131.2 A
Nominal secondary current (ONAF)	524.9 A
Nominal secondary current (ONAN)	393.7 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

– Nominal values for the current
- Primary winding — I_{ONAN} 131.2 A — I_{ONAF} 175.0 A
- Secondary winding — I_{ONAN} 393.7 A — I_{ONAF} 524.9 A

– Nominal values for the power
  - Primary winding P_{ONAN} 7.5 MVA P_{ONAF} 10 MVA
  - Secondary winding P_{ONAN} 7.5 MVA P_{ONAF} 10 MVA

– Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV U_{ONAF} 33 kV
  - Secondary winding U_{ONAN} 11 kV U_{ONAF} 11 kV

– Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6 R_{ONAF} 6
  - Secondary winding R_{ONAN} 6 R_{ONAF} 6

– Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN/ONAF

– Transition temperatures ONAN – ONAF and ONAF – ONAN
  - Transition from ONAN to ONAF $\Theta_{ONAN\text{-}ONAF}$ 75 °C
  - Transition from ONAF to ONAN $\Theta_{ONAF\text{-}ONAN}$ 50 °C

– Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
  - ONAF mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$

– Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
  - ONAN mode $\tau_{oil} = 210$ min, $\tau_{winding} = 10$ min
  - ONAF mode $\tau_{oil} = 150$ min, $\tau_{winding} = 7$ min

– Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode $x = 0.8$, $y = 1.3$
  - ONAF mode $x = 0.8$, $y = 1.3$

– Sample time for actual values for current and ambient temperature
  - $t_{sample} = 900$ s (15 minutes)

– Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
  - ONAN mode $(H{\cdot}g_r)_{ONAN} = 26$ °C
  - ONAF mode $(H{\cdot}g_r)_{ONAF} = 26$ °C

Whitchurch T1

The following important nameplate details have been gathered for the power transformer T1 located at substation Whitchurch.

General

Supplier	Brush Transformers Limited
Year of manufacturing	2010
Serial number	83128/1
Cooling	ONAF/ONAN

Power

Nominal primary power (ONAF)	10 MVA
Nominal primary power (ONAN)	7.5 MVA

Voltage

Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV

Current

Nominal primary current (ONAF)	175.0 A
Nominal primary current (ONAN)	131.2 A
Nominal secondary current (ONAF)	524.9 A
Nominal secondary current (ONAN)	393.6 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

– Nominal values for the current
  - Primary winding I_{ONAN} 131.2 A I_{ONAF} 175.0 A
  - Secondary winding I_{ONAN} 393.6 A I_{ONAF} 524.9 A

– Nominal values for the power
  - Primary winding P_{ONAN} 7.5 MVA P_{ONAF} 10 MVA
  - Secondary winding P_{ONAN} 7.5 MVA P_{ONAF} 10 MVA

– Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV U_{ONAF} 33 kV
  - Secondary winding U_{ONAN} 11 kV U_{ONAF} 11 kV

– Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6 R_{ONAF} 6
  - Secondary winding R_{ONAN} 6 R_{ONAF} 6

– Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN/ONAF

– Transition temperatures ONAN – ONAF and ONAF – ONAN
  - Transition from ONAN to ONAF $\Theta_{ONAN\text{-}ONAF}$ 75 °C
  - Transition from ONAF to ONAN $\Theta_{ONAF\text{-}ONAN}$ 50 °C

– Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$
  - ONAF mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$

– Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
  - ONAN mode $\tau_{oil} = 210$ min, $\tau_{winding} = 10$ min
  - ONAF mode $\tau_{oil} = 150$ min, $\tau_{winding} = 7$ min

– Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode $x = 0.8$, $y = 1.3$
  - ONAF mode $x = 0.8$, $y = 1.3$

– Sample time for actual values for current and ambient temperature
  - $t_{sample} = 900$ s (15 minutes)

- Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
  - ONAN mode $(H \cdot g_r)_{ONAN}$ = 26 °C
  - ONAF mode $(H \cdot g_r)_{ONAF}$ = 26 °C

Yockingsgate T1

The following important nameplate details have been gathered for the power transformer T1 located at substation Yockingsgate.

General

Supplier	Ferranti Limited
Year of manufacturing	1964
Serial number	152785
Cooling	ONAN

Power

Nominal primary power (ONAN)	7.5 MVA

Voltage

Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV

Current

Nominal primary current (ONAN)	131.3 A
Nominal secondary current (ONAN)	394 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

- Nominal values for the current
  - Primary winding I_{ONAN} 131.3 A
  - Secondary winding I_{ONAN} 394 A
- Nominal values for the power
  - Primary winding P_{ONAN} 7.5 MVA
  - Secondary winding P_{ONAN} 7.5 MVA
- Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV
  - Secondary winding U_{ONAN} 11 kV
- Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6
  - Secondary winding R_{ONAN} 6
- Cooling system (ONAN, ONAF, ONAN/ONAF)
  - ONAN
- Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode k_{11} = 0.5, k_{21} = 2.0, k_{22} = 2.0
- Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]

- ONAN mode τ_{oil} = 210 min, $\tau_{winding}$ = 10 min

– Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode x = 0.8, y = 1.3

– Sample time for actual values for current and ambient temperature
  - t_{sample} = 900 s (15 minutes)

– Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]
  - ONAN mode $(H{\cdot}g_r)_{ONAN}$ = 26 °C

Liverpoolroad T1

The following important nameplate details have been gathered for the power transformer T1 located at substation Liverpoolroad.

General	
Supplier	Brush
Year of manufacturing	2001
Serial number	78210/1
Cooling	ONAN
Power	
Nominal primary power (ONAN)	7.5 MVA
Voltage	
Nominal primary voltage	33 kV
Nominal secondary voltage	11 kV
Current	
Nominal primary current (ONAN)	131.2 A
Nominal secondary current (ONAN)	393.6 A

Based on the previous details and on the IEC 60076-7, the following set of parameters is used to describe the transform in the thermal model.

– Nominal values for the current
  - Primary winding I_{ONAN} 131.2 A
  - Secondary winding I_{ONAN} 393.6 A

– Nominal values for the power
  - Primary winding P_{ONAN} 7.5 MVA
  - Secondary winding P_{ONAN} 7.5 MVA

– Nominal values for the voltage
  - Primary winding U_{ONAN} 33 kV
  - Secondary winding U_{ONAN} 11 kV

– Ratio of load losses at rated current to no-load losses [IEC 60067-7, Table E.1]
  - Primary winding R_{ONAN} 6
  - Secondary winding R_{ONAN} 6

– Cooling system (ONAN, ONAF, ONAN/ONAF)

- ONAN

– Thermal model constants k_{11}, k_{21} and k_{22} [IEC 60067-7 – Table 5]
  - ONAN mode $k_{11} = 0.5$, $k_{21} = 2.0$, $k_{22} = 2.0$

– Time constants for oil (τ_{oil}) and winding ($\tau_{winding}$) [IEC 60067-7 – Table 5]
  - ONAN mode $\tau_{oil} = 210$ min, $\tau_{winding} = 10$ min

– Oil (x) and winding (y) exponents [IEC 60067-7 – Table 5]
  - ONAN mode $x = 0.8$, $y = 1.3$

– Sample time for actual values for current and ambient temperature
  - $t_{sample} = 900$ s (15 minutes)

– Hotspot temperature rise above top-oil temperature in steady state [IEC 60067-7, Table E.1]

APPENDIX B
Real time thermal rating model

This chapter describes the background of the dynamic thermal model for two windings power transformers. The proposed real-time thermal rating (RTTR) model or dynamic rating system (DRS) is based on the IEC 60076-7 /1/ standard.

The IEC loading guide contains information on the thermal behaviour of power transformers and provides guidelines for modelling this behaviour. It also describes the impact of the way of loading the transformer. In that respect, the behaviour of or change in top-oil and hotspot temperature are of importance.

The top-oil temperature is the temperature of the oil on top of the transformer winding. In case of ONAN and/or ONAF cooled power transformers, thus the oil circulation inside the transformer is due to natural convection, the top-oil temperature is assumed to be equal to the oil near the top of the transformer tank.

The hotspot temperature is the temperature of the hottest location of a transformer winding. The allowed maximum hotspot temperature determines the allowed maximum transformer loading. This maximum temperature or upper limit depends on the applied insulation material.

Transformer suppliers limit the values of allowed top-oil and hotspot temperatures. The hot-spot is the maximum temperature occurring in any part of a winding insulation system and it is assumed to represent the thermal limitation of the transformer /2/. Exceeding these limits will result in additional reduction of the transformer life. The nominal hot-spot temperature for transformers with normal paper is typically taken to be 98°C, representing nominal thermal ageing of the paper. Moreover the limits depend on the size and type of the power transformer as well as on the type of overloading. The loading guide given in IEC 60076-7 /1/ standard presents general limits for distribution, medium power and large power transformers. For the medium power transformers investigated in this study, these general limits are presented in Table B-1.

Table B-1: Current and temperature limits applicable to loading beyond nameplate rating /IEC 60076-7, Table 4/

Types of loading	Medium power transformers
Normal cyclic loading	
Current (p.u.)	1.5
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	120
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)	140
Top-oil temperature (°C)	105
Long-time emergency loading	
Current (p.u.)	1.5
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	140
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)	160
Top-oil temperature (°C)	115
Short-time emergency loading	
Current (p.u.)	1.8
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	160
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)	180
Top-oil temperature (°C)	115

It should be noted that the temperature and current limits are not intended to be valid simultaneously. The current may be limited to a lower value than that shown in order to meet the temperature limitation requirement. Conversely, the temperature may be limited to a lower value than that shown in order to meet the current limitation requirement.

B.1 Loading beyond nameplate rating

The effects and dangers related to loading a transformer beyond its nameplate is also described in the loading guide /1/. This section summarizes the text from the loading guide, more details can be found in the loading guide itself. Several extracts have been taken from /1/ and presented in italic.

The normal life expectancy is a conventional reference basis for continuous duty under design ambient temperature and rated operating conditions. The application of a load in excess of nameplate rating and/or an ambient temperature higher than design ambient temperature involves a degree of risk and accelerated ageing.

B.1.1 General Consequences

The consequences of loading a transformer beyond its nameplate rating are as follows /1/:

- a *The temperatures of windings, cleats, leads, insulation and oil will increase and can reach unacceptable levels.*
- b *The leakage flux density outside the core increases, causing additional eddy-current heating in metallic parts linked by the leakage flux.*

c As the temperature changes, the moisture and gas content in the insulation and in the oil will change.

d Bushings, tap-changers, cable-end connections and current transformers will also be exposed to higher stresses which encroach upon their design and application margins.

As a consequence, there will be a risk of premature failure associated with the increased currents and temperatures. This risk may be of an immediate short-term character or come from the cumulative effect of thermal ageing of the insulation in the transformer over many years.

B.1.2 Short-time emergency loading

Short-time increased loading will result in a service condition having an increased risk of failure. Short-time emergency overloading causes the conductor hot-spot to reach a level likely to result in a temporary reduction in the dielectric strength. However, acceptance of this condition for a short time may be preferable to loss of supply. This type of loading is expected to occur rarely, and it should be rapidly reduced or the transformer disconnected within a short time in order to avoid its failure. The permissible duration of this load is shorter than the thermal time constant of the whole transformer and depends on the operating temperature before the increase in loading; typically, it would be less than half-an-hour.

B.1.3 Long-time emergency loading

This is not a normal operating condition and its occurrence is expected to be rare but it may persist for weeks or even months and can lead to considerable ageing. The calculation rules for the relative ageing rate and per cent loss of life are based on considerations of long-term risks.

B.2 Thermal model

The thermal model as described in the loading guide /1/ is based on a simplified model of a transformer winding in a tank filled with oil. It is based on several assumptions; see also Figure B-1:

a The oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode

b As a first approximation, the temperature rise of the conductor at any position up the winding is assumed to increase linearly, parallel to the oil temperature rise, with a constant difference g_r between the two straight lines (g_r being the difference between the winding average temperature rise by resistance and the average oil temperature rise in the tank)

c The hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding as described in point b), because allowance has to be made for the increase in stray losses, for differences in local oil flows and for possible additional paper on the conductor. To take into account these non-linearity's, the difference in temperature between the hot-spot and the top-oil in tank is made equal to $H \times g_r$, that is, $\Delta\theta_{hr} = H \times g_r$, in which H is defined as the hot-spot factor.

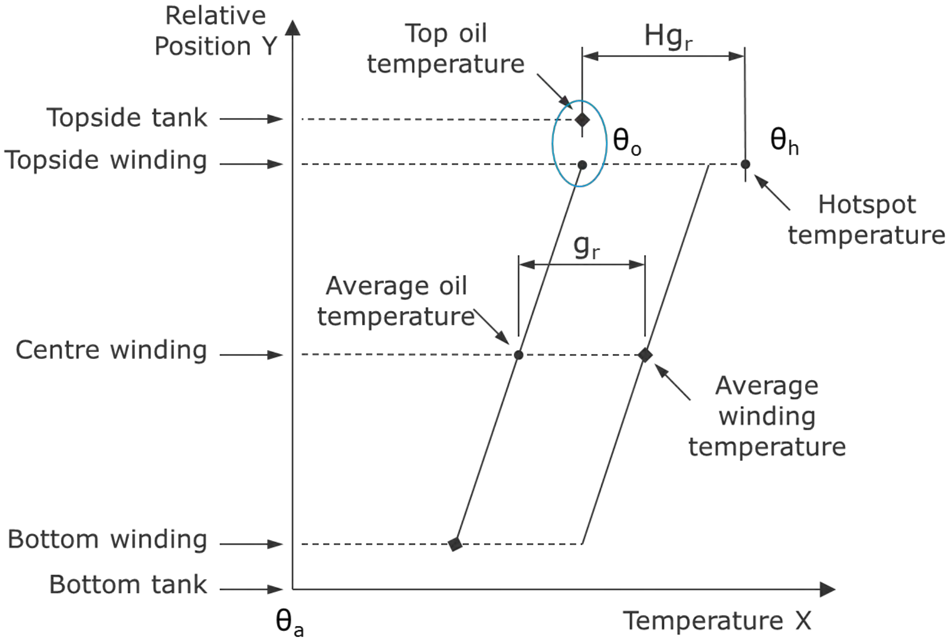


Figure B-1: Thermal diagram

The temperature increase is caused by internal and external sources. Examples of external sources are ambient temperature, solar radiation, wind and rain. Examples of internal sources are transformer losses due to the magnetic core, the windings, connections, tap changer and bushings. Losses in the magnetic core are typically due variation of alternating flux in the magnetic circuit and thus voltage related. Losses in the winding are typically ohmic losses and eddy currents and thus load related. Other losses have been neglected in the derivation of the thermal model.

The losses can be seen as a flow of heat into the transformer, similar to a current source into an electric circuit. The transformer has a thermal capacitance and thermal resistivity which affects the heat flow from the source through the transformer to the outside world. As a result, the thermal process can be modelled using an equivalent electric model, see Figure B-2.

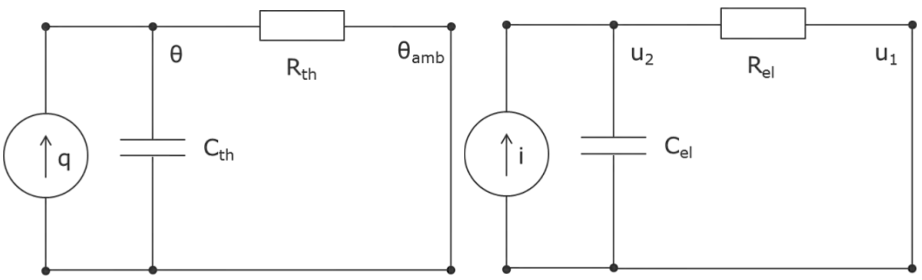


Figure B-2: Thermal transformer model (left) and its electrical analogue (right)

Using this analogy, the thermal model of the transformer is developed, see Figure B-3.

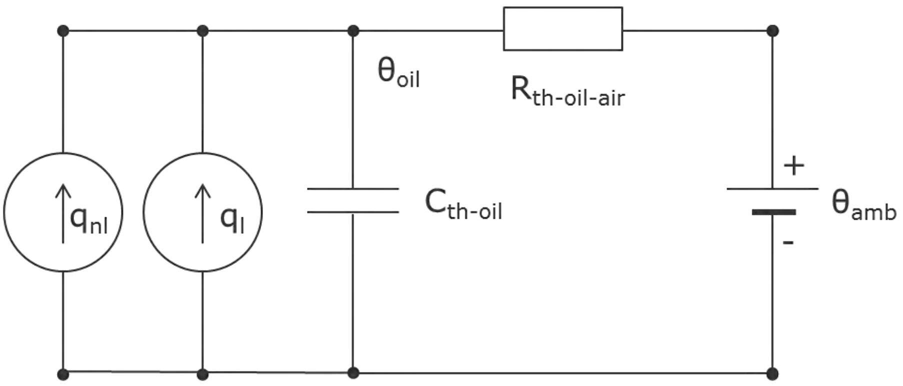


Figure B-3: Thermal model used in IEC 60076-7

From Figure B-3, the following equation can be derived:

$$q_{nl} + q_l = C_{th-oil} \cdot \frac{d\theta_{oil}}{dt} + \frac{\theta_{oil} - \theta_{amb}}{R_{th-oil-air}} \tag{B-1}$$

in which

q_{nl}:	non-load-related losses
q_l:	load-related losses
$C_{th\text{-}oil}$:	thermal capacitance of the oil
$R_{th\text{-}oil\text{-}air}$:	thermal resistivity of the oil (abbreviated as R_{th} from this point onwards)
Θ_{oil}:	top-oil temperature
Θ_{amb}:	ambient temperature

B.2.1 Steady state loading

As can be seen from formula (B-1), there is a time-depending part and non-time-depending part. For steady state, the time-depending part is equal to zero and the equation simplifies into

$$q_{nl} + q_l = \frac{\theta_{oil} - \theta_{amb}}{R_{th}} \tag{B-2}$$

Using

$$\Delta\theta_0 = \theta_{oil} - \theta_{amb} \tag{B-3}$$

K is defined as the ratio between the actual current and rated current:

$$K = \frac{I}{I_{rated}} \tag{B-4}$$

Furthermore, the relation between the actual losses ql and the losses at rated current is described by

$$q_l = K^2 q_{l,rated} \tag{B-5}$$

This leads to the following formula for the top-oil increase over ambient temperature, in which the ambient temperature is considered to be constant:

$$\Delta\theta_o = R_{th}\left(q_{nl} + K^2 \cdot q_{l,rated}\right) \quad \textbf{(B-6)}$$

The top-oil temperature increase at rated loading can be calculated according to

$$\Delta\theta_{or} = R_{th}\left(q_{nl} + q_{l,rated}\right) \quad \textbf{(B-7)}$$

From (B-7) the thermal resistance R_{th} can be determined

$$R_{th} = \frac{\Delta\theta_{or}}{q_{nl} + q_{l,rated}} \quad \textbf{(B-8)}$$

By defining the Ratio of load losses at rated current to no-load losses by

$$R = \frac{q_{l,rated}}{q_{nl}} \quad \textbf{(B-9)}$$

and combing this with (B-6) leads to

$$\Delta\theta_o = \Delta\theta_{or}\left(\frac{1 + R \cdot K^2}{1 + R}\right) \quad \textbf{(B-10)}$$

From this, the top-oil temperature can be calculated according to

$$\theta_o = \theta_{amb} + \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x \quad \textbf{(B-111)}$$

in which x is the oil-exponent which is an empirically derived value used to approximately take the effects of change in resistance with change in load into account.

The hotspot temperature can be derived from the top-oil temperature by adding a certain transformer dependent factor, as mentioned in the introduction of this section and shown in Figure B-1: the hot-spot temperature rise above top-oil temperature in the tank. Finally the hotspot temperature under steady state conditions can be calculated according to the following equation:

$$\theta_h = \theta_a + \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x + H \cdot g_r \cdot K^y \quad \textbf{(B-12)}$$

in which y is the winding exponent which is an empirically derived value used to take the effects of changes in resistance and viscosity with changes in load into account.

B.2.2 Dynamic loading

In practical situations, the transformer will never be operating in steady state. Varying load current and ambient temperature will affect the hotspot temperature dynamically. With time-varying load and ambient conditions, the thermal capacitance of the transformer will start playing a role, see equation (B-1). IEC 60076-7 presents an example of dynamic loading, which is copied into this document in Figure B-4. It clearly shows that the increase in hotspot temperature (Θ_h) and top-oil temperature (Θ_o) is not instantaneous with the increase in the loading, but it takes time before the maximum temperature is reached.

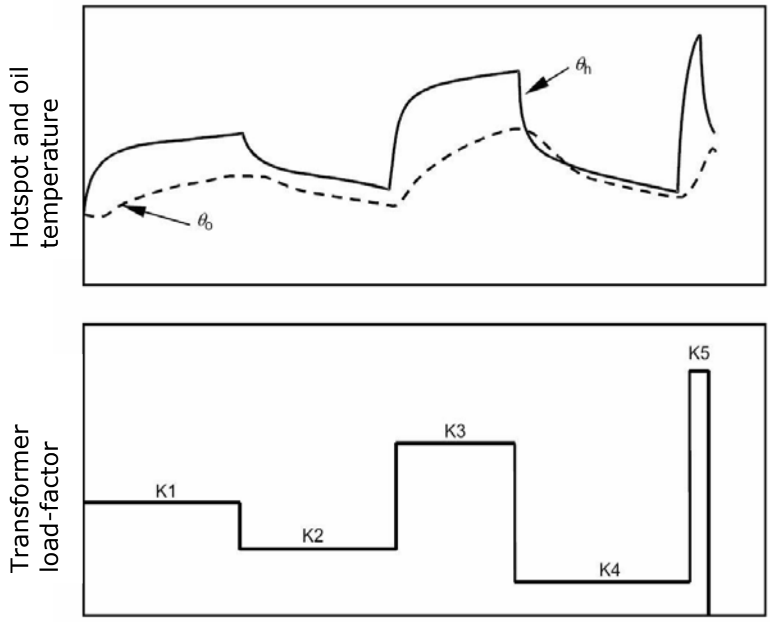


Figure B-4: Temperature responses to step changes in the load current (in which K1 till K5 are different load-factors) /1/

The rise of the top-oil temperature as function of time can be calculated by

$$\theta_o(t) = \theta_{amb} + \Delta\theta_{oi} + \left(\Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x - \Delta\theta_{oi}\right) \cdot f_1(t) \quad \textbf{(B-13)}$$

The rise of the hot-spot temperature as function of time can be calculated by

$$\Delta\theta_h(t) = \theta_o(t) + \Delta\theta_{hi} + (H \cdot g_r \cdot K^y - \Delta\theta_{hi}) \cdot f_2(t) \quad \textbf{(B-14)}$$

The decrease of the hot-spot temperature as function of time can be calculated by

$$\Delta\theta_h(t) = \theta_{amb} + \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x + \left(\Delta\theta_{oi} - \Delta\theta_{or} \cdot \left(\frac{1 + R \cdot K^2}{1 + R}\right)^x\right) \cdot f_3(t) + \\ + H \cdot g_r \cdot K^y \quad \textbf{(B-15)}$$

The function $f_1(t)$ describes the relative increase of the top-oil temperature rise, the function $f_2(t)$ describes the relative increase of the hot-spot-to-top-oil gradient and the function $f_3(t)$ describes the relative decrease of the top-oil-to-ambient gradient and are defined as

$$f_1(t) = 1 - e^{\left(\frac{-t}{k_{11} \cdot \tau_0}\right)} \quad \textbf{(B-16)}$$

$$f_2(t) = k_{21.} \left(1 - e^{\left(\frac{-t}{k_{22} \cdot \tau_w}\right)}\right) - (k_{21} - 1) \cdot \left(1 - e^{\left(\frac{-t}{\left(\tau_0 / k_{22}\right)}\right)}\right) \quad \textbf{(B-17)}$$

$$f_3(t) = e^{\left(\frac{-t}{k_{11} \cdot \tau_0}\right)} \qquad \textbf{(B-18)}$$

In the above equations, k_{11}, k_{21} and k_{22} are transformer thermal model constants, τ_w is the winding time constant and τ_o is the oil time constant.

The time constant of the oil is highly determining the thermal behaviour of the winding. The time constant depends on the thermal capacity of the oil, the core, the windings and the way the heat is transported to the surroundings.

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