Short-time Overloading of Power Transformers

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KTH Electrical Engineering

Master Thesis
Stockholm, Sweden 2011

XR-EE-ETK 2011:012

KTH Electrical Engineering

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MASTER THESIS

ROYAL INSTITUTE OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING

ABB CORPORATE RESEARCH

VÄSTERÅS

June, 2011

Foreword and Acknowledgments

This report accounts for the master thesis work “short-time overloading of power transformers” performed between February 2011 and June 2011 in a co-operation between the school of electrical engineering at the Royal Institute of Technology KTH in Stockholm and ABB Corporate Research in Västerås. It was performed during 20 weeks as a Degree Project in Reliability Centred Asset Management for Electrical Power Systems, and as a part of Degree Program in Electrical Engineering (Electric Power Engineering), 300 credits. The work was funded by ABB Corporate Research.

At KTH my examiner was Patrik Hilber. At ABB Corporate Research my supervisors were Robert Saers and Nilanga Abeywickrama.

I would like to show my gratitude to Robert Saers for guidance in the project, productive discussion and recommendation, careful review of the report, and valuable comments about the work. I am also thankful for his support and encouragement.

I am very thankful to Nilanga Abeywickrama which helps me during the work and gives me excellent and constructive comments. I would like also to thank him for the careful review of the report.

I thank Bengt-Olof Stenestam and Björn Weström for the data they shared with me.

Finally, and significantly I would like to express my love to my sons Didan and Dabin for bringing happiness and joy to my life and thank my wife who did not let them be alone during my studies.

Abstract

The power transformer is one of the most expensive components in an electrical transmission and distribution network. The temperature inside a power transformer varies with the load. The higher the operating temperature the faster the degradation of paper-press board insulation, consequently the remaining life of the transformer decreases. In order to keep the temperature under a safe limit, thermal models for predicting the hottest spot temperature in a transformer based on the load, cooling factors and ambient conditions have been developed and currently used in practice.

In this project, a thermal model stipulated by the IEC standard is evaluated. The evaluation is carried out using the experimental results obtained at varying load current on a 40MVA-OFAF-cooled transformer equipped with both fibre-optic sensors and oil temperature indicator, and a 63MVA-ONAF-cooled transformer equipped with oil temperature indicator. The model parameters are obtained from a normal heat-run test performed by the transformers manufacture. It can be shown that the response of the Difference equations method to the load variations is better than the Exponential method.

A model Using Difference equations method and based on the internal cooling variations is proposed in this thesis. However, the calculated hot-spot temperature is not in a good agreement with the measured hot-spot temperature during rapid load increase.

A proper result for the hot-spot temperature calculation using Difference equations method with ONAN cooling mode is obtained, although the cooling class of the transformer is OFAF. The calculated hot-spot temperature is compared to the measured hot-spot temperature to evaluate the model. The Difference equations method with ONAN cooling mode never underestimates the hot-spot temperature more than 3℃ under a normal loading period. For the particular overloading situation the underestimation is 9.9 % of the time period that is less accurate comparing to the normal loading period. The rate of occurrence of the underestimation is 7.7% for the Difference equations method with OFAF cooling mode during the normal loading situation and 13.8 % during the overloading situation. However, the Difference equations method with OFAF cooling mode never underestimates the hot-spot temperature more than 10℃ during the normal loading and overloading situations.

Improvements are still required in order to predict the hot-spot temperature accurately using the Difference equations method under various dynamic loading conditions.

Results indicate that the calculated top-oil temperatures are either underestimated or overestimated. For accurate hot-spot temperature calculations, it is hence recommended to use the measured top oil temperature.

Keywords

Power transformer, loss of life, thermal model, hot-spot temperature, evaluation, verification

List of Symbols

Symbol	Description
θ_h	winding hot-spot temperature [°C]
θ_o	top-oil [in tank] temperature [°C]
$\Delta\theta_o$	top-oil [in tank] temperature rise [K]
$\Delta\theta_h$	hot-spot temperature rise [K]
$\Delta\theta_{o,start}$	temperature rise of top-oil in tank at start [K]
$\Delta\theta_{h,start}$	hot-spot temperature rise above top-oil [in tank] temperature at start [K]
θ_a	ambient temperature [°C]
$\Delta\theta_{o,r}$	top-oil temperature rise in the tank above ambient temperature at rated losses [K]
$\Delta\theta_{o,f}$	final top-oil temperature rise in the tank above ambient temperature at rated losses [K]
$\Delta\theta_{h,r}$	hot-spot temperature rise above ambient temperature at rated current [K]
H	hot-spot factor
R	ratio load losses at rated current to no-load losses
K	load factor, ratio load current to rated current (actual load to rated load)
x	oil exponent which represents the exponential power of the total losses versus oil temperature rise
y	winding exponent which represents the exponential power of the current versus winding temperature rise
g_r	average winding to average oil(in tank) temperature gradinet at rated current [K]

τ_o	top-oil time constant $[\min]$
τ_w	winding time constant $[\min]$
k_{21}, k_{22}, k_{11}	thermal constants for various cooling modes, characterize the oil flow.
L	loss of insulation life [days]
B_p	overshoot factor of the function $f_2(t)$ which is the maximum value of the function.
T_p	overshoot time duration that takes for $f_2(t)$ to reach the value of B_p from load start
$f_2(t)$	normalized time variation of hot-spot temperature rise above top-oil at load increase
K	Kelvin (is a unit of measurement for temperature)
°C	Celsius (is a unit of measurement for temperature)
q_{fe}	heat generated by iron (no-load) losses [W]
q_l	heat generated by the load losses [W]
q_w	heat generated by the winding losses [W]
C_o	thermal capacitance of the oil [J/°C]
R_o	thermal resistance of the oil [°C/W]
C_h	thermal capacitance of the winding [J/°C]
R_h	thermal resistance of the oil [°C/W]

List of used abbreviations

Abbreviation	Description
TEC	Transformer electronic control, or intelligent monitoring system
OF	Forced circulation through cooling equipment, thermo-siphon flow in windings
OD	Forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings
ONAN	Oil Natural Air Natural, without pump and fans
ONAF	Oil Natural Air Forced, without pump for oil, with fans for air
OFAF	Oil Forced Air Forced, with pump for oil and fans for air
OFAN	Oil Forced Air Natural, with pump for oil

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1 Introduction

1.1 Background

One of the most important components as well as one of the most cost-intensive components in a power network is the power transformer. Efficient transmission and distribution of electricity through different voltage levels is made possible by using power transformers. Any outage of this component may affect the reliability of the entire network and has considerable economic impact on the system. Thus, the reliability and the profitability of this component are intensely researched.

Good planning and accurate controlling have to be taken into account in order to use power transformers efficiently. Normally, transformers are designed to operate within its name plate ratings. However, power transformers are occasionally loaded beyond nameplate ratings because of existing possible contingencies on the transmission lines, any failure or fault in power systems, or economic considerations.

Overloading of power transformers causes an increase of operation temperature. It has been a fact that the operating temperature has an influence on the aging of power transformers. As the operating temperature varies with the loading of a transformer, it is essential to model the heat transfer characteristics between windings and oil in order to make a prediction of the hot-spot temperature in the transformer as a function of the load, taking the cooling characteristics into account.

At ABBs intelligent monitoring system a thermal model for power transformers based on the standard IEC 354 is used to predict top-oil and hot-spot temperatures [5], [6] and [24]. There is also a thermal model for power transformers stipulated by the new version of the IEC standard, i.e. IEC 60076-7, for the same purpose [2].

This text serves as a result of a master thesis project aimed at studying temperature calculations in power transformers during short-time overloading. The thesis is performed as a co-operation between the school of electrical engineering at the Royal Institute of Technology KTH in Stockholm and ABB Corporate Research in Västerås.

1.2 Thesis outline

Chapter 2 describes the loading characteristics of power transformers, overloading consequences and the limitations.

Chapter 3 presents various approaches for calculating hot-spot temperature. A thermal model based on the top-oil temperature is suggested. Three methods based on the thermal model are presented for calculating top-oil and hot-spot temperatures.

Chapter 4 shows and analyses the top-oil temperature, the hot-spot temperature and the loss of life calculations based on the IEC standard methods.

Chapter 5 shows the model deviations. An attempt is made to improve the model and a number of simulations based on various cooling modes are performed.

Chapter 6 evaluates and discusses the results of hot-spot temperature calculations in detail. The comparison is made between the methods.

Chapter 7 concludes the thesis.

Chapter 8 proposes future works.

1.3 Aim

The main aim of this thesis is to evaluate the validity of a thermal model stipulated by the IEC standard to predict the hot-spot temperature and the top-oil temperature in power transformers. The model predictions of the temperature using various methods are compared with the empirical data from transformer measurements obtained at load varying current containing overloading time periods.

1.4 Method

A literature survey is done to identify existing thermal models for power transformers. The empirical and measured data, during a specific case of loading a power transformer beyond the name-plate rating, is used to verify the thermal model. This verification is performed by temperature calculations using various methods in MATLAB. The calculated results are compared with the measured data obtained from fibre-optic temperature measurement equipment, which was installed in a power transformer for experimental reasons.

2 Transformer Overloading and Limitations

In the power systems, transformers may be occasionally loaded above their name plate ratings in a response to emergency or contingency conditions. The overloading may also occur because of economic considerations. It is no need to install extra transformer utilizing the overloading capability of the existing transformer. However, there are risks and consequences when the power transformer is overloaded beyond its rated nameplate which can lead to failures. The failures can be both short-term failures or/and long-term failures. The accelerated aging is one of the main consequences of overloading power transformers. In addition, there are temperature and load limitations presented in this chapter in order to operate transformer in a safe condition.

2.1 Types of loading

Load conditions of transformers can be classified into four types [1], [2], which are described in the following sections.

2.1.1 Normal life expectancy loading

Normal life expectancy occurs when the power transformer is operated with continuous hot-spot temperature of 98℃ for non-thermally upgraded paper and 110 ℃ for thermally upgraded paper. However, it is permissible to operate the transformer over this temperature for a short time during a period of time, providing that the transformer has operated for a long time under this temperature [1].

The exact end of life of transformers are unknown, however according to IEC [2] there are different predictions for insulation life depending on mechanical properties such as, Retained Tensile Strength and/or retained Degree of Polymerization. For a 200 retained degree of polymerization in insulation and at the reference temperature of 110℃ the normal insulation life can be 17.12 years considering thermally upgraded insulation.

2.1.2 Planned overloading

This type of loading occurs when the utility operator plan to overload the transformer during specific time that is more typical in utility operation. The hot-spot temperature may rise to 120-130℃ during this type of loading. No-system outage, planned repetitive loads and shorter life expectancy are the characteristics of this type of loading [1]. For this loading type, calculations can be made to define the time period in which the acceptable loss of life can be achieved.

2.1.3 Long-time overloading

In this type of overloading, the transformer is operated beyond its nameplate rating for a long time, from several hours to several months, carrying emergency loads. It might

occur one or two times during the normal life of the transformer. Long-time overloading occurs because of an outage in a power system or contingencies on the transmission system.

However, the risk of failure is greater than the planned overloading and the hot spot temperature can rise to 120°C -140°C under operation [1]. For this loading type calculations can be made, in order to evaluate the acceptable loss of insulation life during a specific load cycle.

2.1.4 Short-time overloading

Short-time overloading is heavy loading of a transformer during a short time that causes the temperature to increase rapidly and exceed the limits defined by the name-plate ratings. In this type of loading, the hot-spot temperature may rise to 180°C for a short time period [1] with severe loss of insulation life. The main characteristics of this type of loading are [1]:

- Highly unlikely operation conditions on the transmission system.
- It is expected to occur one or two times over the normal life of a transformer and it usually last for a short-time (less than half an hour) [1], [14].
- The risk of failure even is greater than long time overloading, due to the bubble and gas formation in the oil.

Overloading transformers for a short-time may be acceptable when there is an outage or loss of power supply in the system. According to the IEC standard [2], the acceptable time duration of this type of load is less than the thermal time constant of the transformer and depends on the operation temperature before increasing the loads, typically half an hour. To avoid any failure, either this type of loading should be decreased or the transformer should be disconnected within that time [2].

Historically, many users have relied on the short-time overloading capacity of transformers during emergency conditions in the system. In the economical point of view and during particular conditions it may be necessary to use up to 50% or even more of the corresponding transformer lifespan to prevent a serious shutdown [13].

However, to perform heavy overloading of transformers, reliable information is required to predict the hot-spot temperatures and loss of insulation life. The methods with are used to perform these predictions are presented and discussed in chapter three. Furthermore, the risks have to be considered when using the short-time overloading capacity of transformers. Some of these risks are stated in the next section.

2.2 Risks of overloading

If the transformer is loaded according to nameplate ratings, it will have a normal lifespan. However, it depends on the design of transformers; different manufacture uses different limits for operational temperature. Otherwise, by operating the transformer beyond its nameplate or in an ambient temperature higher than what it is designed for, the aging of the transformer is accelerated more than that in the case of normal loading. The aging rate is doubled for every (6-8)℃ hot-spot temperature increase [1], [14]

There are risks associated with overloading transformers especially for short-time overloading. For undesirable events, the magnitude of the risks depends on the quantity of free gas, moisture content of oil and insulation, and voltage. Some of these undesirable events [1] [2] are:

- Gas bubbling from the insulated conductors and insulation adjacent to the metallic structural parts may reduce and jeopardize the dielectric strength.
- Temporary deterioration of the mechanical properties at higher temperatures could reduce the short-circuit strength.
- Mechanical or dielectric failures due to thermal expansion of conductors, insulation materials and structural parts.
- Increasing pressure in the bushings could result in leaking gaskets, loss of oil and extreme dielectric failure.
- Increased resistance in the contacts of the tap-changer that may result from an increasing of oil-decomposition products.
- Breaking of very high current in the tap-changer could be risky.
- Oil expansion in the tank may occur when the top-oil temperature rises above the standard limitation.
- The voltage regulation through the transformer may increase due to the increased apparent power loading and possibly dropping power factor.

2.3 Load carrying capacity

Utilizing the thermal inertia of a transformer and the relation between the deterioration and the temperature, the transformer can be loaded beyond the nameplate ratings for a limited period of time, even with natural cooling and without modifying the thermal output [9].

However, the maximum permissible load must not exceed the maximum value specified by the manufacture.

The magnitude of the continuous load carrying capacity depends on its rating, the temperature of the cooling medium and the considerations from the user regarding the ageing of the insulations used in the transformer. Moreover, the magnitude and the duration of the periodic load carrying capacity depends on the constructional features of the transformer, operational conditions during overloading and the magnitude of time constants.

By fully utilizing the thermal inertia of transformers and using the full capacity of the cooling system, it is possible to achieve 20 to 25 years of service life for transformers even with varying loads that occasionally exceed their rated values [9].

2.4 Aging of transformer insulation

The insulation system of a power transformer mainly consists of oil and paper which undergoes aging. The used paper is mainly Cellulose based and the degree of polymerization (DP) represents the mechanical strength of the fibre, and in turn the paper itself.

Aging or deterioration of the insulation is dependent on temperature, moisture content, and oxygen content and acid content. However, the main factor affecting the aging is the temperature of paper insulation as the impact of the other factors are minimized by using modern oil preservation systems [1]. The considered temperature in the calculation of aging is the hot-spot temperature which is the maximum temperature in the winding insulation [1], [2].

Sudden increase of load results in an increased hot-spot temperature and consequently causes the thermal decomposition of cellulose. According to Montsinger [22] the rate of deteriorating of the insulation condition is doubled for each (5-10) ℃ increase in continuous operating temperature. Thus, the combination of temperature and time depolymerise the cellulose insulation, and this process can eventually cause the termination of insulation life and consequently the termination of the transformer life.

Based on Arrhenius Chemical Reaction Rate Theory [17], [22], and [14] the rate of change of a measured property can be expressed as follows:

$$R = A' e^{-B/T} \qquad (1)$$

Where, A' and B are empirical constants, and T is the temperature in [K].

According to references [17], [22], and [14] all aging rate data can be fit into Eq. (1). Thus, the insulation life in [per-unit] or [h] can be written as follows:

$$L = A e^{B/T} \qquad (2)$$

Where, *A* is the constant derived from the insulation life at a hot-spot temperature of 110℃ and *B* is the aging rate slope. It has been decided to choose a single value for B for all types of cellulose which is the 15000 and a single value for A which is the 9.8×10^{-18} [1], [2], [14], [18], [19] and [20].

Based on Eq. (2), the per-unit life of the insulation is expressed as follows [1], [14]:

$$\text{per unit life} = 9.8\times10^{-18}\times e^{\left(15000/(\theta_h+273)\right)} \quad (3)$$

where, θ_h is the hot-spot temperature in [℃].

2.4.1 Relative aging rate

The relative aging rate is the rate at which the aging of paper insulation for a hot-spot temperature is reduced or accelerated compared with the aging rate at a reference hot-spot temperature [2], which is the rate at 110℃ according to the reference [1].

For thermally upgraded paper, which is chemically modified to improve the stability of the cellulose structure, the relative aging rate *V* is

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h+273}\right)} \quad (4)$$

where, 110℃ is the rated hot-spot temperature for thermally upgraded paper.

And for non-thermally upgraded paper, the relative aging rate *V* is

$$V = 2^{\left(\theta_h-98\right)/6} \quad (5)$$

where, 98℃ is the rated hot-spot temperature for non-thermally upgraded paper.

In [15] and [16] it is shown that, the depolymerisation process with time and temperature in the thermally upgraded paper is much slower than non-thermally paper.

In Eq. (4), the relative aging rate for the thermally upgraded paper is higher than unity for hot-spot temperatures greater than 110℃, and it is less than unity for hot-spot temperatures less than 110℃ [2].

Moreover in Eq. (5), the relative aging rate for the non-thermally upgraded paper is higher than one for hot-spot temperatures which are greater than 98℃, and it is less than one for hot-spot temperatures which are less than 98℃ [2].

The reference hot-spot temperature of 110℃ is based on the summation of three temperatures, namely; 30℃ (average ambient temperature), 65℃ (average winding temperature rise) and 15℃ (allowance for the hot-spot gradient over average temperature winding) [1].

2.4.2 Loss of insulation life

The loss of life in a time period is equivalent to life consumed by the insulation in hours or days during that time. Mathematically, loss of insulation life is calculated by integrating the relative aging rate over certain period of time. The loss of life L in continuous-time form [2] and over a period of time, say from t_1 to t_2, is

$$L = \int_{t_1}^{t_2} V dt \qquad (6)$$

and, in discrete-time form [2] and over a certain number of time intervals, it is

$$L = \sum_{n=1}^{N} V_n t_n \qquad (7)$$

where, V_n is the relative aging over a certain period of time n, t_n is the time interval of the period, and N is the total number of intervals.

2.5 Influence of ambient temperature

An important factor that affects the loading capability of the transformer is the ambient temperature, since it adds to the temperature rise of any load in determining the operation temperature. The temperature of air conducting the radiators or heat exchangers usually is considered as the ambient temperature. For every 1℃ ambient temperature decrease, the load capacity can increase by 1% without any loss of life or vice versa [14], [1].

In the IEEE standard [1], a 24-hour average ambient temperature of 30℃ is the base for transformer ratings and it is a standard ambient temperature in the IEEE guide while IEC standard uses 20℃ as average ambient temperature. According to IEEE standard [1] whenever the actual ambient temperature is measured, it should be averaged over a 24 hour period in order to use it for calculations for loading capability of transformers.

Dealing with short-time loads, the ambient temperature can be taken as the maximum daily temperature for the month considered and it is recommended to increase it by further 5℃ [1].

2.6 Temperature and load limitations

In order to operate a power transformer in a safe condition, loading and permitted heating of the active parts should be limited. The hot-spot temperature is the most concerned operational temperature in the transformer [3], [25].

The impending danger of a high hot-spot temperature is the evolution of free gas bubbles within the insulation during overloading. However, according to a survey presented in [10], 80% of the responses believed that there is no a single safe limit for hot-spot temperature during overloads. Moreover, most of responders believed that the factors which would influence the temperature to generate free gas bubbles influence the selection of a safe limit for the hot-spot temperature [10]. The factors can be:

- Moisture content of the insulation.
- Gas content of the oil.
- Hydrostatic pressure at the hot-spot conductor.
- The high temperature time-duration.
- Risk considerations, e.g. number of its occurrence and its impact on the operation system.

Table 1 shows suggested limits of temperature and load for loading above nameplate with 65℃ average winding rise according to IEEE [1].

Table 1: Temperature and load limits.

Top-oil temperature	110℃
Hot-spot temperature	180℃
Maximum loading	200%

Table 2 shows suggested maximum temperature limits for the short-time overloading that may cause reasonable loss of insulation life, according to IEEE [1].

Table 2: Maximum temperature limits for short-time overloading.

Top-oil temperature	110℃
Hot-spot temperature for the insulated conductors	180℃
Hot-spot temperature for other metallic parts	200℃

Table 3 shows the load and temperature limits for short-time overloading according to IEC [2].

Table 3: Temperature and load limits according to IEC.

Top-oil temperature	115℃
Hot-spot temperature for windings and metallic parts adjacent to insulation material	160℃
Hot-spot temperature for other metallic parts in contact with oil, paper and glass fibre materials	180℃
Maximum loading	150%

2.7 Temperature limitations of ancillary components

Loading transformers beyond their name plate ratings can have significant adverse effect on ancillary components. Some of these effects are presented in the following sections.

2.7.1 Bushings

Overloading of bushings is less severe compared to transformer winding overloading. However, the possible unwanted events [1] are

- Increasing pressure in the bushings.
- Aging of gasket materials.
- Gassing from increasing of temperature above 140℃.
- Increasing dielectric losses that cause thermal runaway.
- Heating in metallic flanges.
- Thermal deterioration may cause unusual increases in power factor.

Bushings have a predicted life less than that of the transformer insulation. However, the bushing life can be equivalent to the transformer insulation life as their operating temperature is less than the rated top-oil temperature in most cases, while the transformer rated current are less than the bushing rating current in many cases [1].

Table 4 shows the temperature and the overload limits considering the coordination of bushings with transformer according to IEEE [1]. However, the limits apply to oil-impregnated, paper-insulated and capacitance-graded bushings only.

Table 4: Temperature and load limits in bushings.

Top-oil temperature of the Transformer	110℃
Hot-spot temperature for bushing insulation	150℃
Current (of rated bushing current)	200%
Ambient temperature	40℃

2.7.2 Load tap-changers

The calculations done in the IEEE [1] show that the LTC can carry overloading as high as 132% of the rated load according to name plate at an ambient temperature of 30℃, before the contact temperature of the LTC rises to 120℃.

Calculations of temperature overloading of the transformer can be made more precise if the effect of tap changer connections is considered. Furthermore, according to IEC [8] the temperature rise limits shall apply to every tapping at the appropriate tapping power, tapping voltage and tapping current in the temperature calculations, if the tapping range exceeding $\pm 5\%$ or for the transformer rated power larger than 2.5 MVA.

2.7.3 Bushing-type current transformers

The ambient to the bushing-type current transformers is the top-oil which has the maximum temperature limit of 105℃ at rated output for 65℃ average winding rise transformers according to IEEE [1]. During overloading the top-oil temperature as well as the secondary current in the current transformer increase with associated temperature rise. The fact that the top-oil temperature at rated output is often below 105℃ reduces the severity of the current transformer overloads [1].

2.7.4 Insulated lead conductors

The same hot-spot temperature limits for windings apply for leads as well, since similar materials for insulation are normally used in both cases. Generally, the temperature rise of the insulated lead conductors does not limit the capability of the transformer in overloading conditions [1].

3 Temperature Calculation Methods

The hot-spot temperature, i.e. the maximum temperature of the winding insulation system, is assumed to be the thermal limitation of loading of transformers. Besides, other parts of the transformer like bushings, current transformers and tap-changers have to be chosen in a way that they do not put any further restriction on the load ability of the transformer [1].

The hot-spot temperature is used to evaluate a relative value for the rate of thermal aging and the percentage of life consumed in a particular time period. In general, these calculations are performed during overloading situations.

Mathematical models are presented in the IEC standard [2], [24] to estimate the top-oil temperature in the tank and the hot-spot temperature in the windings in steady state and transient conditions. In this chapter, the thermal model used to calculate the top-oil and hot-spot temperatures is presented.

3.1 Hot-spot temperature rise

The hot-spot temperature rise above top-oil temperature can be defined either by direct measurement during heat-run test or calculated from normal heat-run test data. Fig. 1 shows a simplified transformer thermal diagram which illustrates the main temperature distribution along the winding and the oil in the tank [2], where H is the hot-spot factor and g_r is the average winding to average oil temperature gradient at rated current.

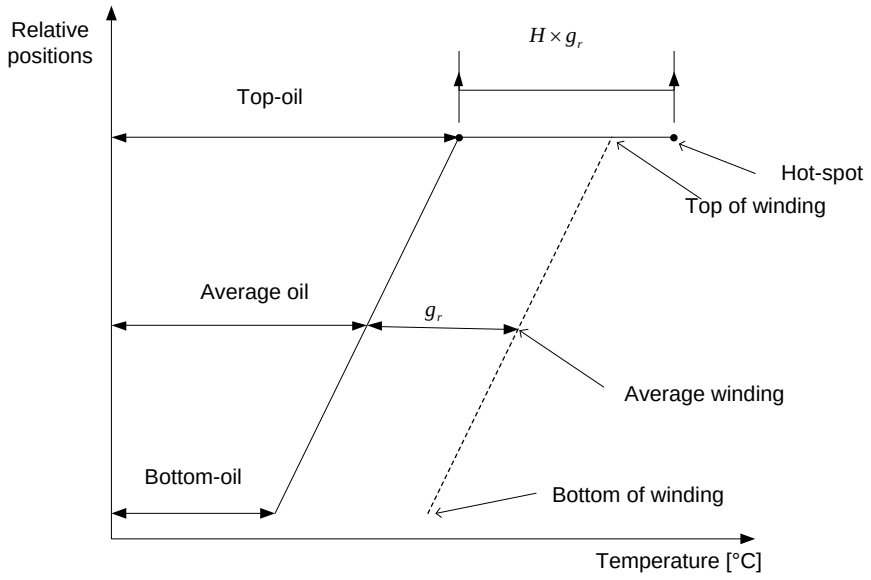

Fig. 1: The simplified thermal diagram of transformers that shows the temperature distribution along the winding height and the oil in the tank.

The following simplifications are performed in the thermal diagram [2]:

- Linear increase of oil temperature inside the tank from bottom to top, independent of the cooling mode.
- Parallel to the oil temperature rise, the temperature of the conductor up to the winding increase linearly. Thus, the winding temperature rise and the oil temperature rise appear as two parallel lines and the difference between these two lines is constant which is equal to g_r.
- Because of the increase in stray losses, the hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding. The difference in temperature between the hot-spot and the top-oil in tank is defined as the hot-spot temperature rise at rated current, i.e. $\Delta\theta_{h,r} = H \times g_r$.

In Fig. 1, the following temperature values can be measured:

- Bottom-oil temperature measured from oil temperature indicator.
- Average winding temperature determined by resistance measurement.
- Top-oil temperature measured from oil temperature indicator.

To find the hot-spot temperature, the hot-spot temperature rise is added to the top-oil temperature, that is

$$\theta_h = \theta_o + \Delta\theta_h \qquad (8)$$

where, θ_o is the top-oil temperature and $\Delta\theta_h$ is the hot-spot temperature rise in [℃].

The top-oil in the tank is considered as the reference oil instead the top-oil in the winding, as it is normally measured during a heat run test, in calculating hot-spot temperature. However, measurements have shown that the top-oil temperature inside a winding, depending on the cooling, is up to 15K higher than the mixed top-oil temperature inside the tank [2].

3.1.1 Hot-spot factor

The hot-spot factor H is a winding specific which varies within the ranges 1.0 to 2.1 depending on the size, winding design, and short-circuits impedance of the transformer. The hot-spot factor can be defined either by direct measurement or calculations based on the fundamental loss and heat transfer principles. During heat-run tests, the hot-spot factor is taken as the ratio of the gradient of the hot-spot temperature rise for the hottest-spot and the average winding to average oil gradient. Thus, the hot-spot factor can be determined by the following equation [2]:

$$H = \frac{\Delta\theta_{h,r}}{g_r} \ . \qquad (9)$$

However, its value is considerably dependent on the design, thus measurements should be performed on the transformer to determine an accurate hot-spot factor [8].

3.2 Hot-spot temperature measurement

Hot-spot temperature is measured directly by installing fibre optic sensors in each winding where the measurement is required. There may be gradients of more than 10K between different locations in the top of normal transformer winding; therefore more than three sensors are required [2]. Consequently, a compromise should be done between the number of probes needed to find optimum solution and the additional efforts and costs caused by fibre optic probes.

Usually, the maximum leakage field and the highest surrounding oil temperature are on the conductors near the top of the winding, therefore the hottest-spot temperature can be considered to be located on the top conductors. However, measurements in [3] show that the hottest-spot temperature may be present in the lower conductors. Therefore, the sensors have to be distributed on the first few winding discs, seen from the top. The location of the sensors can be defined by separate loss/thermal calculations.

3.3 Hot-spot temperature calculations

It is essential to accurately predict the hot-spot temperature at each moment at real-time dynamic loading of power transformers. The best option is to directly measure the hot-spot temperature though a fibre optic sensor. However, it may not be practical for the existing transformers, and may not be cost effective for new transformers [21]. Thermal models are developed to predict the hot-spot temperature described by a time function and a dependent variable that varies with the change in ambient temperature and load current.

In such models, hot-spot temperature is assumed to be equal to the sum of the ambient temperature, the top-oil temperature rise above ambient temperature, and the hot-spot temperature rise above top-oil temperature. Fig. 2 shows a block diagram that illustrates different ways to calculate the hot-spot temperature with different approaches.

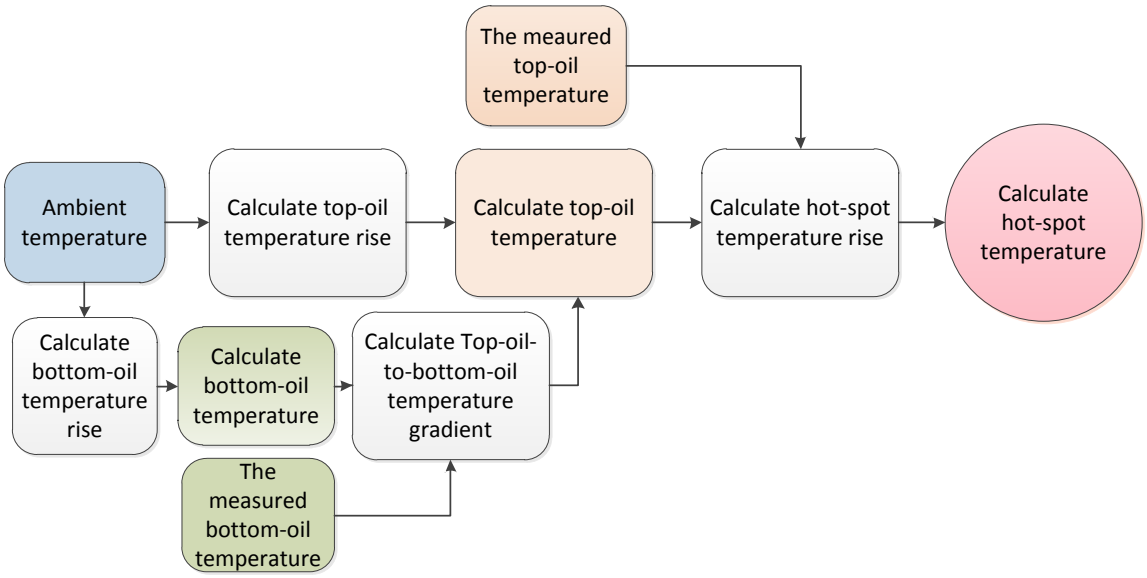

Fig. 2: An Illustration diagram showing various approaches for calculating hot-spot temperature.

The transformer parameters, time-constants and thermal constants associated with the heat transfer characteristics between winding, oil and other parts should be available in order to proceed with the calculations. Normally, these parameters are obtained during heat-run tests. If the measured top-oil temperature is available, it can be added directly to the calculated hot-spot temperature rise to calculate the hot-spot temperature. Alternatively, using measured bottom-oil temperature, the top-oil temperature can be calculated and thereby the hot-spot temperature.

The top-oil temperature can be calculated theoretically using transformer parameters, load factor and the ambient temperature. However, in this project the hot-spot temperature, calculated from either measured top-oil temperature or calculated top-oil temperature, is considered. The top-oil temperature is calculated using the top-oil temperature rise at rated current, transformer parameters, and the ambient temperature.

3.3.1 Hot-spot temperature at steady state

In steady state, the top-oil temperature rise is proportional to the total transformer losses. Thus, top-oil temperature rise is mathematically presented as follows [14]:

$$\Delta\theta_o = \Delta\theta_{o,r} \times \left(\frac{P}{P_R}\right)^x = \Delta\theta_{o,r} \times \left(\frac{1+R\times K^2}{1+R}\right)^x \qquad (10)$$

where, P is the total losses in [W], P_R is the total losses at rated load in [W], $\Delta\theta_o$ is the top-oil temperature rise in [K], $\Delta\theta_{o,r}$ is the top-oil temperature rise at rated load in [K],

R is the ratio of load loss to no-load loss at rated load ($K=1$), K is the load in [per-unit] or [%], and superscript x is the oil exponent.

The hot-spot temperature rise over top-oil temperature is proportional to the transformer winding loss considering the winding exponent and the hot-spot temperature rise at rated loss. Thus, the hot-spot temperature rise over top-oil temperature can be presented as follows:

$$\Delta\theta_h = \Delta\theta_{h,r} \times K^y \qquad (11)$$

where, superscript y stands for the winding exponent.

Thus, in steady state, the hot-spot temperature θ_h is calculated as follows [2], [14]:

$$\theta_h = \theta_a + \Delta\theta_o + \Delta\theta_h \qquad (12)$$

where, θ_a is the ambient temperature in [°C] and $\theta_a + \Delta\theta_o = \theta_o$.

By inserting Eq. 10 and 11 into Eq. 12, the following equation is introduced for hot-spot temperature in steady state.

$$\theta_h = \theta_a + \Delta\theta_{o,r} \times \left(\frac{1 + R \times K^2}{1 + R} \right)^x + \Delta\theta_{h,r} \times K^y \quad . \qquad (13)$$

3.3.2 Hot-spot temperature in transient conditions

Thermal models are developed for power transformers to find transient solutions for top-oil and hot-spot temperatures. In this text, a thermal model described by a set of the differential equations is presented and a number of methods based on the IEC standard are suggested to solve the equations.

Two methods are introduced in sections 3.3.1 and 3.3.2, and the third method in section 3.4.1 to calculate the hot-spot temperature in transient conditions.

3.4 A thermal model for power transformers

The thermal model is based on fundamentals and principles of heat transfer theory, lumped capacitance, and the thermal-electrical analogy [11], [25]. Table 5 shows the thermal quantities in analogue to the electrical quantities.

Table 5: Equivalent thermal-to-electrical quantities.

Thermal	Electrical
q : heat transfer rate [W]	i : current [A]
θ : temperature [°C]	U : voltage [V]
R_{th} : thermal resistance [°C/W]	R_{el} : electrical resistance [Ω]
C_{th} : thermal capacitance [J/°C]	C_{el} : electrical capacitance [F]

The thermal laws governing resistances and capacitances are:

$$\theta = R_{th} \times q \quad , \qquad (14)$$

$$q = C_{th} \times \frac{d\theta}{dt} \quad . \qquad (15)$$

The heat capacity and thermal conductivity are the two important thermal parameters of the cooling oil in power transformers. The thermal resistance of the oil is its ability to resist heat flow and the thermal capacitance to store heat. Fig. 3 shows a simplified equivalent thermal circuit for power transformers [11], [25], [26], [27], [28] and [29]. The thermal characteristics of the oil are assumed to be constant in the model.

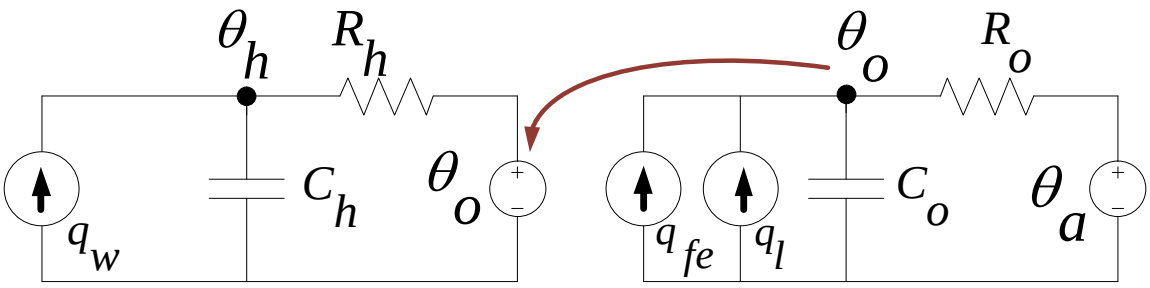

Fig. 3: A simplified thermal circuit model of a power transformer, the copper and iron losses define ideal heat sources, and the ambient air and top-oil temperature define an ideal temperature source (a) represents winding-to-oil model, and (b) represents oil-to-air model.

The parameters used in the model are:

q_{fe} = the heat generated by no-load losses [W]

q_l = the heat generated by the load losses [W]

q_w = the heat generated by the winding losses [W]

C_o = the thermal capacitance of the oil [J/°C]

R_o = the thermal resistance of the oil [°C/W]

C_h = the thermal capacitance of the winding [J/°C]

R_h = the thermal resistance of the winding [°C/W]

The input sources in the thermal model are the iron loss, the copper loss and the ambient temperature.

As the first step the top-oil temperature can be calculated using the oil-to-ambient model in Fig. 3b. Then, the top-oil is considered as the ambient temperature to the winding-to-oil model in Fig. 3a. The top-oil temperature and the hot-spot temperature models are governed by heat transfer differential equations.

It is assumed that the differential equations are linear for all kinds of cooling modes, since the non-linear relationship affects only the final value of any temperature change that occurs, regardless of the cooling mode [2].

Energy balance equation states that energy generated is the sum of the energy radiated and the energy absorbed. Thus, the thermal process can be defined by the following energy balance equation in the differential form [14], [25]:

$$q \times dt = \frac{(\theta - \theta_a)}{R_{th}} \times dt + C_{th} \times d\theta \quad . \tag{16}$$

Based on the Eq. (16), the differential equation for the thermal circuit in Fig. 3a is:

$$\left(q_{fe} + q_l\right) \times dt = \frac{(\theta_o - \theta_a)}{R_o} \times dt + C_o \times d\theta_o \quad . \tag{17}$$

The oil time constant τ_o, which is transformer specific, can be defined by the product of C_o and R_o, thus Eq. (17) can be written as follows:

$$\left(q_{fe}+q_l\right)\times R_o=\tau_o\frac{d\theta_o}{dt}+\left(\theta_o-\theta_a\right)\ . \qquad (18)$$

At steady state $d\theta_o=0$, thus final top-oil temperature rise is defined as follows:

$$\Delta\theta_{o,f}=(q_{fe}+q_l)\times R_o=\Delta\theta_{o,r}\times\left(\frac{1+R\times K^2}{1+R}\right)^x \qquad (19)$$

where, subscript f stands for final.

By inserting Eq. (19) into Eq. (18), a differential equation for the top-oil temperature rise is introduced as follows:

$$\Delta\theta_{o,r}\times\left(\frac{1+R\times K^2}{1+R}\right)^x=\tau_o\frac{d\theta_o}{dt}+\left(\theta_o-\theta_a\right)\ . \qquad (20)$$

The thermal constant k_{11}, which is transformer specific, is stipulated by IEC standard [2] considering different cooling conditions with respect to different types of transformer cooling modes. Thus, Eq. (20) can be written as follows to represent the differential equation for top-oil temperature [2].

$$\Delta\theta_{o,r}\times\left(\frac{1+R\times K^2}{1+R}\right)^x=k_{11}\tau_o\times\frac{d\theta_o}{dt}+\left(\theta_o-\theta_a\right) \qquad (21)$$

where, the input variables into Eq. 21 are θ_a and K.

Fig. 3a shows the thermal model for winding-to-oil heat transfer. The top-oil temperature is either measured from oil temperature indicator or calculated form the oil-to-air model. According to Swift, Moliniski and Lehn [11], the oil temperature affects the hot-spot temperature and not vice versa as it is only about 0.1% of the total copper losses that generates the heat.

Analogy between the oil-to-air model and winding-to-oil model can be summarized in the table 6 [11].

Table 6: Analogy between Oil-to-air model and Winding-to-oil model.

model	Oil-to-air	Winding-to-oil
Ambient fluid	Air	Oil
Fluid movement	By fans	By pumps
Calculated temperature	Top-oil	Hot-spot
Exponent for nonlinearity	x	y

Based on Eq. (16), and the analogy between oil-to-air model and winding-to-oil model in table 6, the differential equation for the thermal circuit in Fig. 3a is

$$q_w \times dt = \frac{(\theta_h - \theta_o)}{R_h} \times dt + C_h \times d\theta_h \ . \qquad (22)$$

At steady state $d\theta_h = 0,$ and by using Eq. (11), the final hot-spot temperature rise is defined as follows:

$$\Delta\theta_{h,f} = q_w \times R_h = K^y \times \Delta\theta_{h,r} \ . \qquad (23)$$

The winding time constant τ_w, which is transformer specific, can be defined by the product of C_h and R_h.

Thus, similar to the top-oil temperature model and using Eq. (23) the winding hot-spot temperature rise over top-oil temperature can be written as the following differential equation:

$$K^y \times \Delta\theta_{h,r} = \tau_w \times \frac{d\Delta\theta_h}{dt} + \Delta\theta_h \ . \qquad (24)$$

According to IEC standard [2], the differential equation for hot-spot temperature rise can be solved as the algebraic sum of the two differential equations considering the thermal relation between the oil and the winding, i.e.

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \ , \qquad (25)$$

where, the differential equations for $\Delta\theta_{h1}$ and $\Delta\theta_{h2}$ are given as the follows:

$$k_{21} \times K^{y} \times \Delta\theta_{hr} = k_{22}\tau_{w} \times \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1}, \qquad (26)$$

$$(k_{21} - 1) \times K^{y} \times \Delta\theta_{hr} = \frac{\tau_{o}}{k_{22}} \times \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \ . \qquad (27)$$

Eq. (25-27) are developed in the standard IEC [2], in order to take into account the fact that it takes some time before the oil circulation adapts its speed to correspond to the increased load level. Thus, thermal constants for both top-oil and the winding hot-spot are included in the equations for hot-spot temperature model. The thermal constants k_{21} and k_{22} are stipulated by IEC standard [2] considering different cooling conditions with respect to different types of transformer cooling modes.

The recommended thermal constants and other thermal characteristics are given in the IEC standard [2]. However, it is recommended to determine them during a heat-run test as they are transformer specific to get accurate result of the model.

When the hot-spot temperature rise is calculated it is added to the top-oil temperature to calculate the hot-spot temperature as follows:

$$\theta_{h} = \theta_{o} + \Delta\theta_{h} \ . \qquad (28)$$

In fact, the cooling medium (oil) has mechanical inertia in addition to the thermal inertia that makes the above equations more complex. Regarding power transformers, this effect is greater for natural-cooling (ON), less for non-directed-flow pumped-oil cooling (OF), and negligible for directed-flow pumped-oil cooling (OD) as well as for distribution transformers [2].

Fig. 4 shows the above differential equations in a block diagram. If the top-oil temperature is measured, the two lower blocks are not needed.

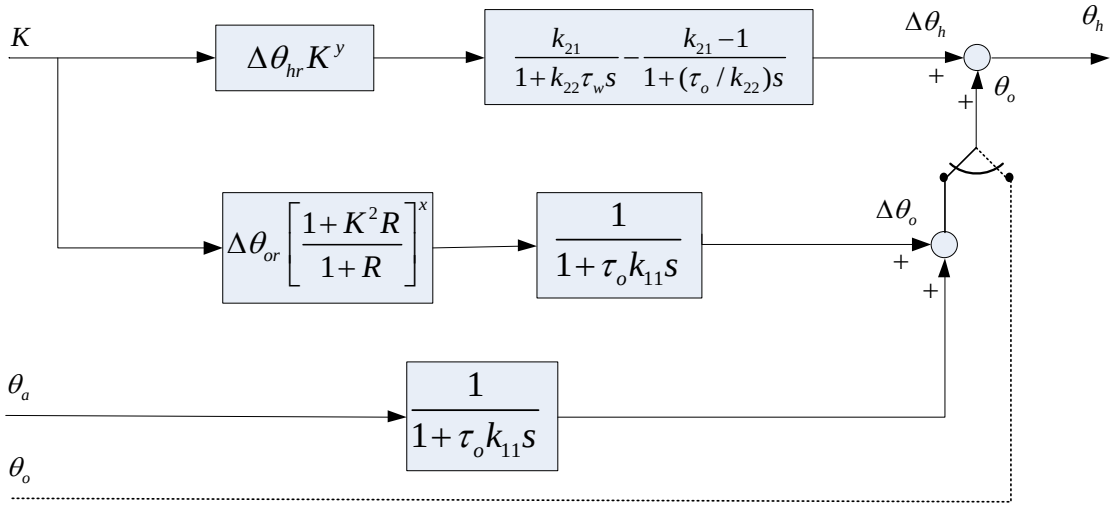

Fig. 4: Block diagram representing the differential equations (the equations are Laplace transformed: the function in terms of the Laplace S). If the measured top-oil temperature (last line) is available it is directly added to the calculated hot-spot temperature (first line) otherwise the blocks in the second line are used to calculate top-oil temperature rise and then added to measured ambient temperature third line, to calculate top-oil temperature.

The second block in the upper most line in the diagram consists of two functions [2]. The first one represents the fundamental hot-spot rise before considering the impact of the oil circulating through the winding and the second represents the impact of the oil-flow passing the hot-spot winding [2].

Two methods are introduced in sections 3.4.1 and 3.4.2, and the third method in section 3.5.1 to calculate the top-oil and hot-spot temperatures solving the differential equations.

3.4.1 Difference equations method

The differential equations described the thermal model can be easily solved if they are e.g. transferred to difference equations. The difference operator *D* is introduced, indicating a small change in the associated variable that corresponds to each time step *Dt*. To get an accurate temperature prediction, the time step should not be greater than half of the smallest time constant in the thermal model [2].

The difference equation for the top-oil temperature in Eq. (21) can be written as:

$$D\theta_o = \frac{Dt}{k_{11}\tau_o} \times \left\{ \left[\frac{1+K^2R}{1+R} \right]^x \times (\Delta\theta_{or}) - (\theta_o - \theta_a) \right\} \qquad (29)$$

Each new value of $D\theta_o$ is added to the old value of θ_o at each time step. Thus, by using Eq. (29) and the value for the top-oil temperature at the time step (n-1), the top-oil at the time step (n) is calculated as follows:

$$\theta_o(n) = \theta_o(n-1) + D\theta_o(n) \quad (30)$$

The difference equations corresponded to the differential equations for the hot-spot temperature in Eq. (26) and (27) are:

$$D\Delta\theta_{h1} = \frac{Dt}{k_{22}\tau_w} \times \left\{ k_{21} \times K^y \times \Delta\theta_{hr} - \Delta\theta_{h1} \right\}, \quad (31)$$

$$D\Delta\theta_{h2} = \frac{Dt}{(1/k_{22})\tau_o} \times \left\{ (k_{21} - 1) \times K^y \times \Delta\theta_{hr} - \Delta\theta_{h2} \right\}. \quad (32)$$

By using Eq. (31) and (32) and the value for hot-spot temperature rise at time step (n-1), the hot-spot temperature rise ($\Delta\theta_h$) at the step (n) is calculated as follows:

$$\Delta\theta_{h1}(n) = \Delta\theta_{h1}(n-1) + D\Delta\theta_{h1}(n), \quad (33)$$

$$\Delta\theta_{h2}(n) = \Delta\theta_{h2}(n-1) + D\Delta\theta_{h2}(n). \quad (34)$$

Thus, at the n^{th} time step and based on Eq. (25) the hot-spot temperature rise is obtained as follows:

$$\Delta\theta_h(n) = \Delta\theta_{h1}(n) - \Delta\theta_{h2}(n). \quad (35)$$

Finally, at the n^{th} time step, the hot-spot temperature is obtained follows

$$\theta_h(n) = \theta_o(n) + \Delta\theta_h(n). \quad (36)$$

This method is suitable for arbitrarily time-varying load and ambient temperature which is applicable for online monitoring [2].

The readers are referred to appendix B for an example using the Difference equations method for calculating the hot-spot and top-oil temperatures [2].

3.4.2 Exponential equations method

In this method, the heat transfer equations are formulated as exponential functions considering the charge and discharge of the thermally RC circuit. Taking into account the transformer oil as heat sink, the temperature rise of the oil can be studied as analogues to a capacitance in the RC circuit.

The basic idea of the top-oil temperature rise model is that an increase in the loading of the transformer results in an increase in the losses and consequently the overall temperature in the transformer. The temperature changes depend on the overall thermal time constant of the transformer which in turn depends on the thermal capacity of the transformer and the rate of heat transfer to the surroundings [23]. Thus, the temperature change can be modelled as a first-order exponential response from initial temperature to the final temperature, as follows [23]:

$$\Delta\theta_o(t) = \Delta\theta_{o,i} + \left(\Delta\theta_{o,f} - \Delta\theta_{o,i}\right) \times \left(1 - e^{-t/\tau_o}\right) \qquad (37)$$

where, subscript i stands for the initial temperature and f for the final temperature.

Eq. (37) is a solution of the following differential equation:

$$\tau_o \frac{d\Delta\theta_o}{dt} = -\Delta\theta_o + \Delta\theta_{o,f}$$, where, $\Delta\theta_o(0) = \Delta\theta_{o,i}$

The final temperature rise depends upon the loading which can be approximated by the following equation [23]:

$$\Delta\theta_{o,f} = \Delta\theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x .$$

Similar to top-oil temperature rise in Eq. (37), an equation for the hot-spot temperature changes can be formulated as an exponential response for the load changes.

$$\Delta\theta_h(t) = \Delta\theta_{h,i} + \left(\Delta\theta_{h,f} - \Delta\theta_{h,i}\right) \times \left(1 - e^{-t/\tau_w}\right) \qquad (38)$$

Eq. (38) is a solution of the following differential equation:

$$\tau_w \frac{d\Delta\theta_h}{dt} = -\Delta\theta_h + \Delta\theta_{h,f}$$, where, $\Delta\theta_h(0) = \Delta\theta_{h,i}$

An explanation of Eq. (38) is that, the I^2R losses in the winding cause the temperature of the winding to increase during both steady state and continuous load. Under continuous load the heat transfer process continues until the heat generated by the winding is equal to the heat taken away by the oil. During the transient conditions the hot-spot temperature rise may change from an initial value to a final value depending on the winding time constant τ_w.

By inserting Eq. (23) in section 3.4 and Eq. (9) in section 3.1.1 into Eq. (38), the following equation for hot-spot temperature rise can be obtained:

$$\Delta\theta_h(t) = \Delta\theta_{h,i} + \left(H \times g_r \times K^y - \Delta\theta_{h,i}\right) \times \left(1 - e^{-t/\tau_w}\right). \quad (39)$$

Thus, for any increase in the load the hot-spot temperature raises to a new value with a time constant characteristics of the winding.

In addition, new thermal constants k_{21}, k_{22} and k_{11} are introduced to the model considering various cooling modes of transformers in the new version of the IEC standard [2], i.e. IEC 60076-7.

Furthermore, in the standard three functions have been introduced using the new thermal constants, namely $f_1(t)$, $f_2(t)$ and $f_3(t)$.

The function $f_1(t)$ represents the relative increase of the top-oil temperature rise, as per unit of its steady state value at increased load, while $f_3(t)$ represents the relative decrease of the top-oil temperature rise as per unit of its steady state value at decreased load. As an example, Fig. 5 shows the shape of the functions $f_1(t)$ and $f_3(t)$ for oil natural air forced, i.e. ONAF, transformers where parameters and constants are recommended by IEC standard [2].

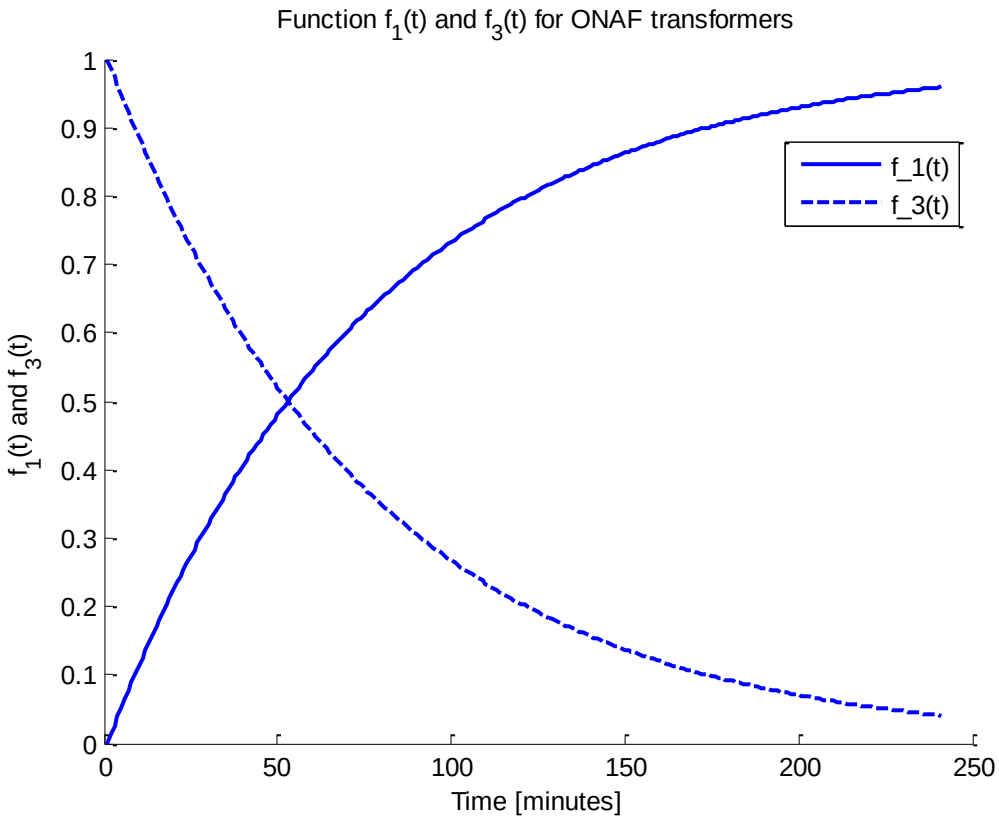

Fig. 5: The functions $f_1(t)$ and $f_3(t)$ generated from the values specified for ONAF transformers ($k_{11}=0.5$ and $\tau_o=150\min$).

The exponential response of the hot-spot temperature rise is improved in the IEC 60076-7 [2] by introducing a function $f_2(t)$ considering the fact that it takes some time before the oil adapts the speed of its circulation with respect to increased step loads [4]. Thus, the function $f_2(t)$ represents normalized time variation of hot-spot temperature rise above top-oil temperature in tank for step increase in load. The graphs of this function can be illustrated by their overshoot factor B_p - and overshoot time duration T_p -values, as shown in Fig. 5, which is plotted for ONAF transformers, as an example, where parameters and constants are taken from the IEC standard [2].

The shapes of function $f_2(t)$ for different power transformer cooling classes and different oil circulation modes (zigzag and axial) are given in [4] and [2].

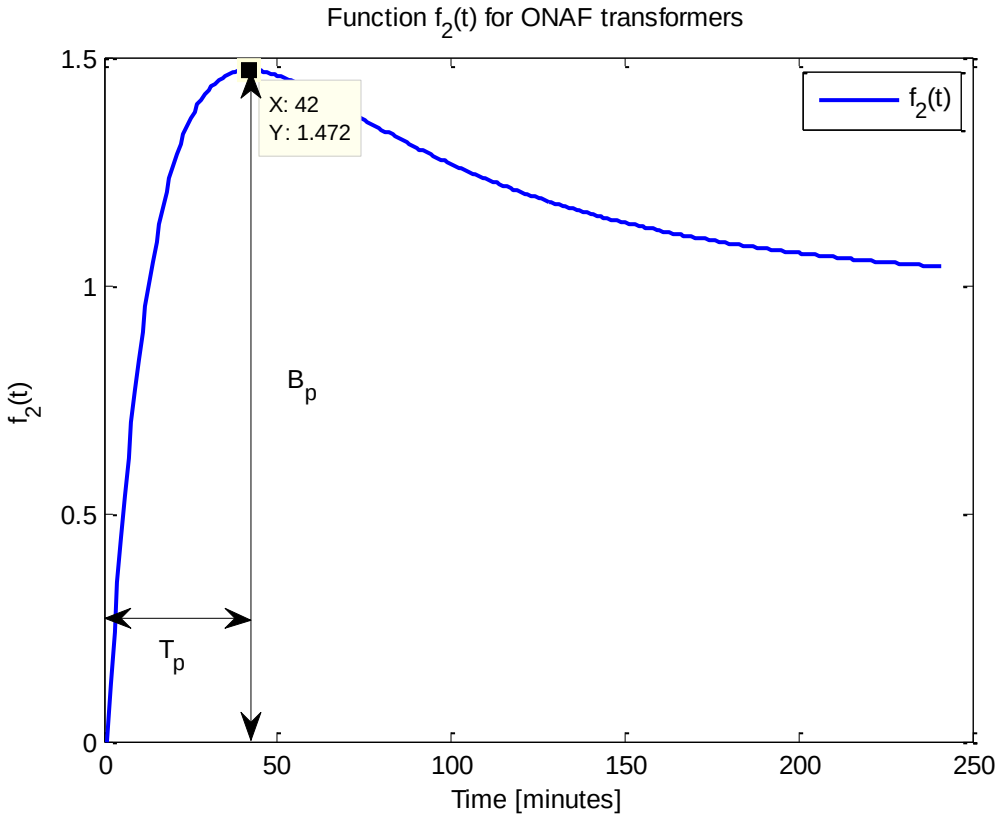

Fig. 6: The function $f_2(t)$ generated from the values specified for ONAF transformers ($k_{21}=2.0$, $k_{22}=2.0$, $\tau_w=7\,\text{min}$, and $\tau_o=150\,\text{min}$), B_p is the overshoot factor, and T_p is the overshoot time-duration.

For increasing step of loads, the top-oil and winding hot-spot temperatures increase to a level corresponding to a load factor of *K* [2].

The top-oil temperature is measured or calculated as follows

$$\theta_o(t)=\theta_a+\Delta\theta_{o,i}+\left\{\Delta\theta_{o,r}\times\left[\frac{1+R\times K^2}{1+R}\right]^x-\Delta\theta_{o,i}\right\}\times f_1(t) \qquad (40)$$

where,

$$f_1(t)=\left(1-e^{-t/k_{11}\times\tau_o}\right).$$

The hot-spot temperature rise is calculated as follows

$$\Delta\theta_h(t) = \Delta\theta_{h,i} + \{H \times g_r \times K^y - \Delta\theta_{h,i}\} \times f_2(t) \quad (41)$$

where,

$$f_2(t) = k_{21} \times \left(1 - e^{-t/(k_{22} \times \tau_w)}\right) - (k_{21} - 1) \times \left(1 - e^{-(t \times k_{22})/\tau_o}\right) .$$

For decreasing step of loads, the top-oil and winding hot-spot temperatures decrease to a level corresponding to a load factor of *K* [2].

The top-oil temperature is either measured or can be calculated as follows

$$\theta_o(t) = \theta_a + \Delta\theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x + \left\{\Delta\theta_{o,i} - \Delta\theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x\right\} \times f_3(t) \quad (42)$$

where,

$$f_3(t) = \left(e^{-t/(k_{11} \times \tau_o)}\right) .$$

The hot-spot temperature rise is calculated as follows

$$\Delta\theta_h(t) = H \times g_r \times K^y . \quad (43)$$

Finally, with $\theta_o(t)$ and $\Delta\theta_h(t)$ from Eq. (40) and (41) respectively for increasing load steps, and Eq. (42) and (43) respectively for decreasing load steps, the hot-spot temperature is calculated as follows:

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h(t) . \quad (44)$$

This method is suitable for determining of the heat-transfer parameters from transformer heat run tests, for simplified scenarios and for load variation appearing to be step functions [2].

The readers are referred to appendix A for an example using the Exponential method for calculating hot-spot and top-oil temperatures [2].

3.4.3 Discussion

The values of the thermal constants (k_{21}, k_{22} and k_{11}), winding time-constant τ_w and oil time-constant τ_o are specific for each transformer which can be measured during a

heat-run test. The recommended parameter values can also be found in the IEC standard [2] for different power transformer cooling classes. There is a calculation method for calculating both τ_w and τ_o [1] and [2]. The readers are referred to appendix D for an example showing the calculation procedure.

The oil cooling ducts in the winding have different paths and consequently the oil will flow through the ducts in different modes (zigzag and axial) [4]. Moreover, the windings represent two basic cases, depending on the width of the radial spacers, either restricted oil flow or unrestricted oil flow.

Tests have been performed on ONAF cooled transformers with different modes of oil circulation [4]. The result of the tests shows that the hot-spot overshoot phenomenon is basically the same for windings with the zigzag cooling and windings with the axial cooling ducts.

However, the same test [4] shows that B_p and T_p have the values of 2.0 and 30 min respectively for windings with restricted oil flow, and 1.5 and 40 min respectively for windings with unrestricted oil flow.

Hot-spot overshoot could be observed in the oil forced air forced, i.e. OFAF, with zigzag cooling, although less pronounced compared to ONAF-cooling. The value of B_p is 1.3 for restricted oil flow and 1.2 for unrestricted oil flow [2], [4].

The stray-loss heating of the top yoke clamp, tie plates and outer core packets show a similar hot-spot temperature overshoot phenomenon as the winding hot-spot temperature [4], [3].

It is recommended, in reference [4], to deal with the dynamic behaviour of hot-spots in the tie plates, outer core pockets and top yoke clamps, at load increase, in the same way as winding hot-spots.

3.4.4 Loss of life calculations

In section 2.4 the loss of life and the relative aging of the insulation have been presented. The loss of life can be calculated knowing the hot-spot temperature of the winding. The calculation is performed by integrating V over certain duration of time, as it is given in Eq. (6) and the equation in differential form is:

$$\frac{dL}{dt} = V \qquad (45)$$

Eq. (45) can be solved by converting to difference equations as follows:

$$DL(n) = V(n) \times Dt, \quad (46)$$

$$L(n) = L(n-1) + DL(n). \quad (47)$$

The readers are also referred to appendix B to see an example using Eq. (4), (46) and (47) for calculating the loss of life.

3.5 ABB's Condition monitoring

In a power system, the load depends on time and its exact values are unpredictable. In order to keep the balance in the system the amount of consumed electricity in any instant of time should be generated somewhere in the system at the same time. Consequently, the load of a power transformer may change continuously.

This means that the transformer can be loaded above its nameplate over a period of time in which an accepted loss of life is consumed. A monitoring system can be used to control the transformer in order to operate it efficiently. The monitoring system predicts and controls the operational temperature to get an acceptable loss of life of the insulation paper in the transformer [5], [6] and [7].

ABBs intelligent monitoring system "TEC" for power transformers is an example of using a thermal model of power transformers for calculating hot-spot temperature in online condition monitoring [5], [6] and [7].

3.5.1 Hot-spot temperature calculations

In TEC, the hot-spot temperature is calculated based on the measured top-oil temperature. The top-oil temperature can also be calculated, if the measured top-oil temperature is unavailable [5], [6] and [7]. The hot-spot temperature is calculated using the Exponential method according to the standard IEC 354 [5], [6], [7] and [24]. According to [6], the following equations can be used to calculate top-oil and hot-spot temperatures.

Top-oil temperature calculation

During load increase, the top-oil temperature is calculated as follows,

$$\theta_o(t) = \theta_a + \Delta\theta_{o,i} + \left\{ \Delta\theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x - \Delta\theta_{o,i} \right\} \times \left(1 - e^{-t/\tau_o} \right). \quad (48)$$

During load decrease, the top-oil temperature is calculated as follows,

$$\theta_o(t) = \theta_a + \Delta\theta_{o,i} \times \left[\frac{1+R\times K^2}{1+R}\right]^x + \left\{\Delta\theta_{o,i} - \Delta\theta_{o,r} \times \left[\frac{1+R\times K^2}{1+R}\right]^x\right\} \times \left(e^{-t/\tau_o}\right) \quad . \qquad (49)$$

Hot-spot temperature calculation

Finally, the hot-spot temperature is obtained by adding the calculated hot-spot temperature rise to either measured or calculated top-oil temperature as follows,

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h \qquad (50)$$

where, $\Delta\theta_h = H \times g_r \times K^y$.

The hot-spot temperature rise is approximated, by setting the winding time constant equal to zero.

The readers are referred to appendix C for an example using the Exponential method of the old version of the IEC standard, i.e. IEC 354, for calculating the hot-spot and top-oil temperatures [6] and [24].

4 Analysis of Standard Models

In this chapter, the top-oil temperature, the hot-spot temperature, and the loss of insulation life under various loading situations are determined using the calculation methods described in chapter 3. Then the results are presented and evaluated by comparing the calculated temperature with the measurement temperature data from two different transformers.

The measurements are performed during a test operation with a dynamic load variation, including both normal loading and overloading periods. The first transformer is 40 MVA-oil forced air forced (OFAF)-cooled, 21/115 kV unit which is denoted by Tr.1 in this report and the second one is 63MVA-oil natural air natural (ONAF)-cooled, 55/140 kV unit which is denoted by Tr.2 in this report. The data is collected during winter time at which the most measured values of the ambient temperatures are below zero or around zero.

According to IEC [2], the ambient temperature for transformer enclosure should be corrected as the transformer experiences an extra temperature rise, about half the temperature rise of the air. Thus, value of $\Delta\theta_{or}$ for the transformer 1, as it is an indoor transformer, should be replaced with $\Delta\theta'_{or}$ as follows:

$$\Delta\theta'_{or} = \Delta\theta_{or} + \Delta(\Delta\theta_{or})$$

where, $\Delta(\Delta\theta_{o,r})$ is the extra top-oil temperature rise.

It is recommended in IEC standard [2] to determine $\Delta(\Delta\theta_{or})$ during heat run-test. However, if it is not available there are recommended values for different type of enclosures which is divided by two to obtain the approximate extra top-oil temperature rise, according to IEC [2].

4.1 Top-oil temperature calculations

According to the IEC standard [2], the actual ambient temperature should be used directly for dynamic load considerations. Furthermore, the standard [2] also recommends using the Difference equations method when both the ambient temperature and the load are the input variables to the model.

In the evaluation of the top-oil temperature model, the top-oil temperature measurements from both transformers are used. The top-oil temperature is calculated during both a normal loading and an overloading period based on the following scenarios:

- The actual ambient temperature is used as the input variable to the model using the Exponential method.
- The ambient temperature is kept constant during the period considered using the Exponential method.
- The actual ambient temperature is used as the input variable to the model using the Differential method.

It is assumed that the capacity of the cooling of the transformer is 100% during operation in all scenarios. A part of the result for the top-oil temperature calculations is presented in this section. The readers are referred to appendix E showing the result of the calculated top-oil temperature during an overloading period for Tr. 1, a normal loading period for Tr.2 and

All scenarios result in deviations between measured and calculated top-oil temperatures, either an underestimation or an overestimation.

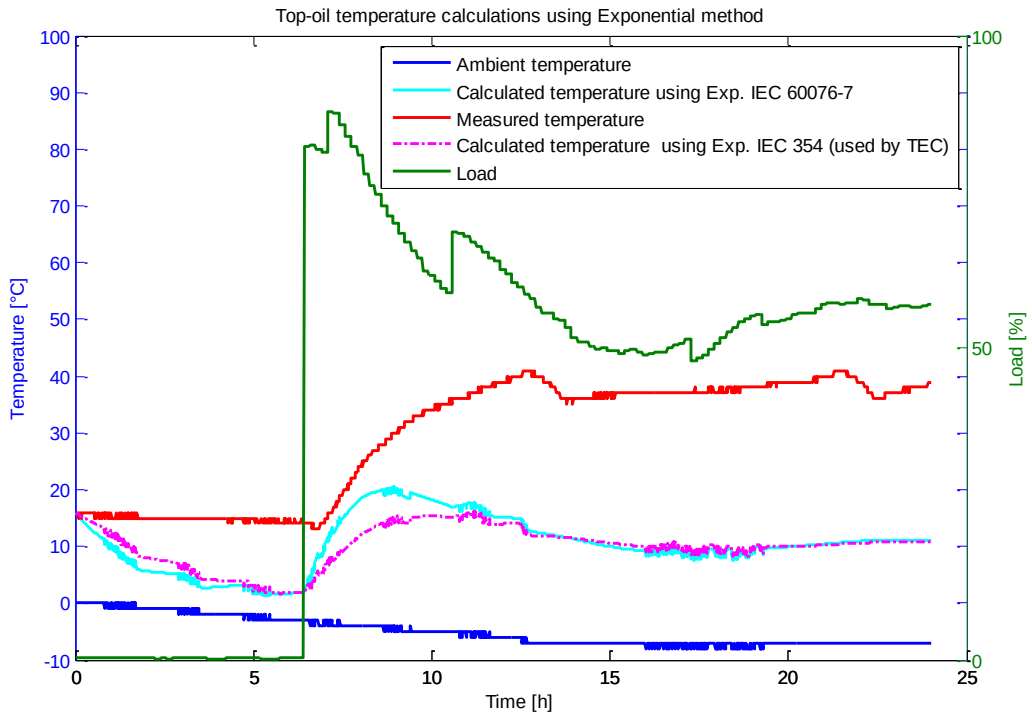

Fig. 7: The calculated top-oil temperature, using the actual ambient temperature as the input variable to the model, for Tr. 1.

Fig. 7 shows the comparison between the measured top-oil temperature of the Tr. 1 and the calculated top-oil temperature considered the first scenario. The top-oil temperatures calculated based on both versions of the standard are low compared to the measured top-oil temperature. Assuming that all the cooling capacity of the

transformer has been used it can be one reason for the temperature underestimation and very low values of the measured ambient temperatures during the test operation can be the second reason. According to Langhame [12] the simplicity of the model is not realistic for very cold weather conditions since the effect of oil viscosity can have a considerable effect at such low temperatures.

Fig. 8 shows the comparison between the measured and calculated top-oil temperatures for Tr. 1, considering the second scenario. In the calculations, a fixed value of 25℃ ambient temperature is used.

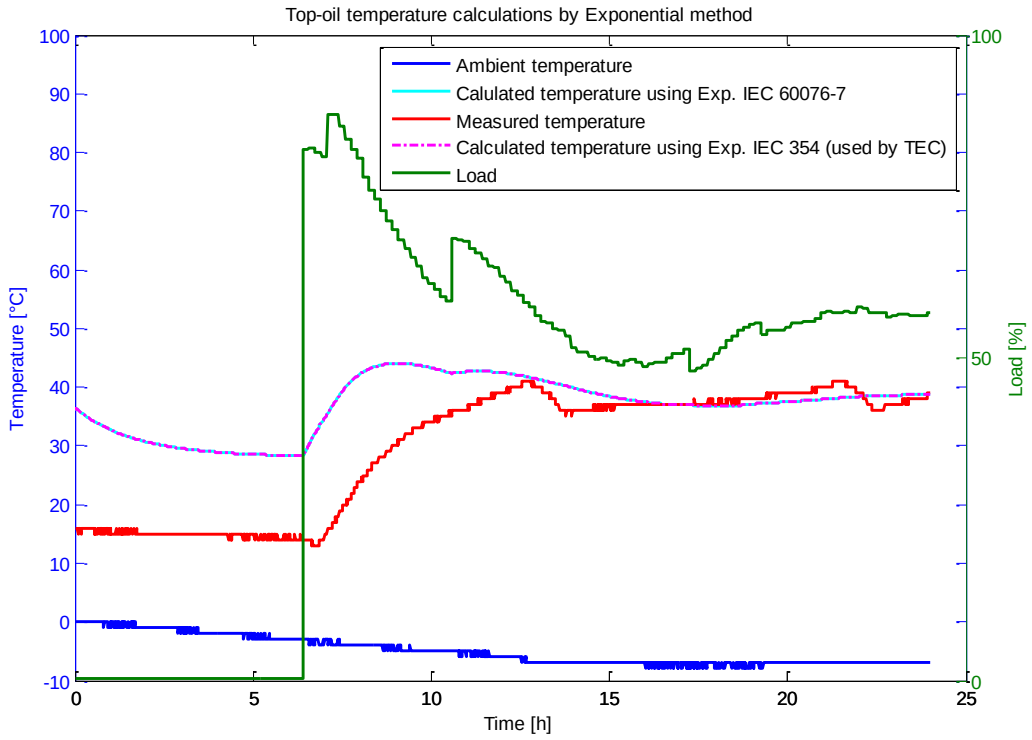

Fig. 8: The calculated top-oil temperature using the Exponential method during normal loading (a constant ambient temperature of 25℃ is used in the calculations), for Tr. 1.

It is shown that the initial value of the calculated top-oil temperature is high and the top-oil temperature is overestimated.

The calculated top-oil temperature from the third scenario is underestimated even more compared to the other scenarios. The result for this scenario is also presented in appendix E.

4.2 Hot-spot temperature calculations

In this section, the hot-spot temperature is calculated based on both measured and calculated top-oil temperatures. The Difference equations method and the Exponential method based on both versions of the IEC standard are used for the determination of the hot-spot temperature. The calculations are performed under both normal loading and overloading situations during a test operation of the power Tr. 1. The power transformer was equipped with fibre-optic sensors in order to measure hot-spot temperature continuously under operation. Hence, this case provides a perfect chance for comparing and verifying the calculated hot-spot temperature by the methods with the actual measured one.

These calculations are performed in accordance with the IEC standard [2]. In the next chapter the model deviations are further analysed and a number of simulations based on the cooling type variations are performed for the calculations in order to achieve better correlation with the measured hot-spot temperature.

4.2.1 Exponential method during normal loading

The hot-spot temperature is calculated using the Exponential equations method during a normal loading period.

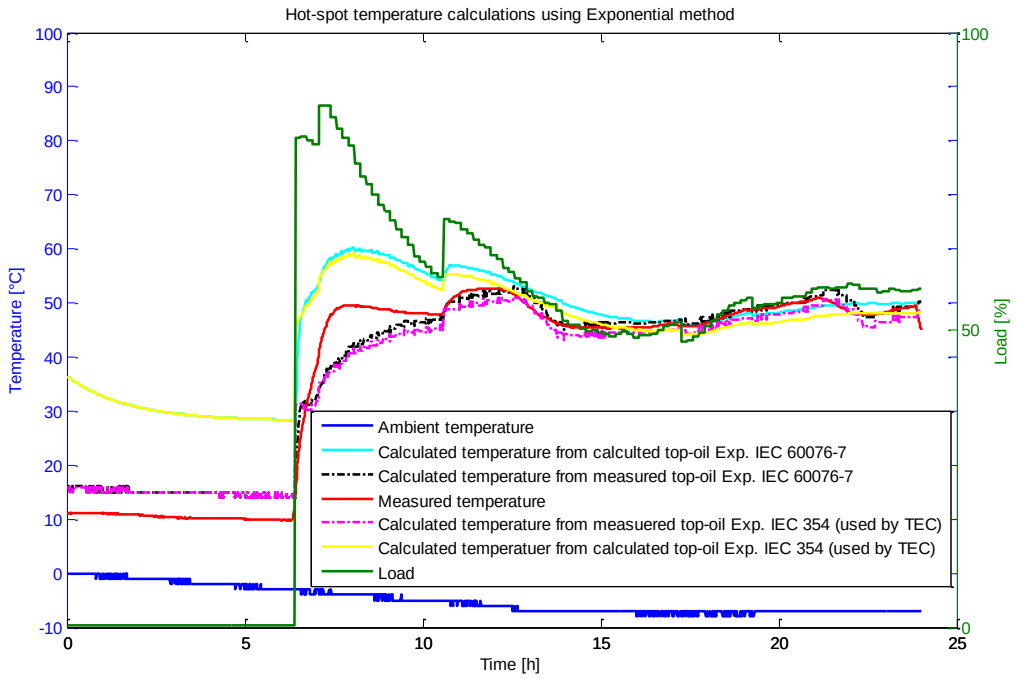

Fig. 9: Hot-spot temperature calculated by the Exponential method during normal loading, Tr. 1 (a constant ambient temperature of 25℃ is used in the top-oil temperature calculations). The winding time constant is set to zero in the Exponential method according to IEC 354.

Fig. 9 depicts a comparison of the measured hot-spot temperature using fibre optic sensors to the calculated hot-spot temperature using the Exponential equations method.

The measurement shows that the hot-spot temperature increases to 50℃ during about 1.5 h, when the load increases rapidly from almost zero to peak value of 87% of the rated load. The calculated hot-spot temperature from measured top-oil temperature is underestimated during the load increase. With corresponding oil-time constant the calculated hot-spot temperature by IEC model is 41℃ for which the measured value is 50℃, a deviation of 9℃. However, this response will be better when the load decreases and becomes more stable, i.e. after about 3h.

Furthermore, the response of the calculated hot-spot temperature from calculated top-oil temperature by both IEC and TEC model is high, for the same rapid increased load step. The calculated hot-spot temperature using IEC 60076-7 model is about 63℃ when the corresponding measured value is 50 ℃, implying a deviation of 13℃.

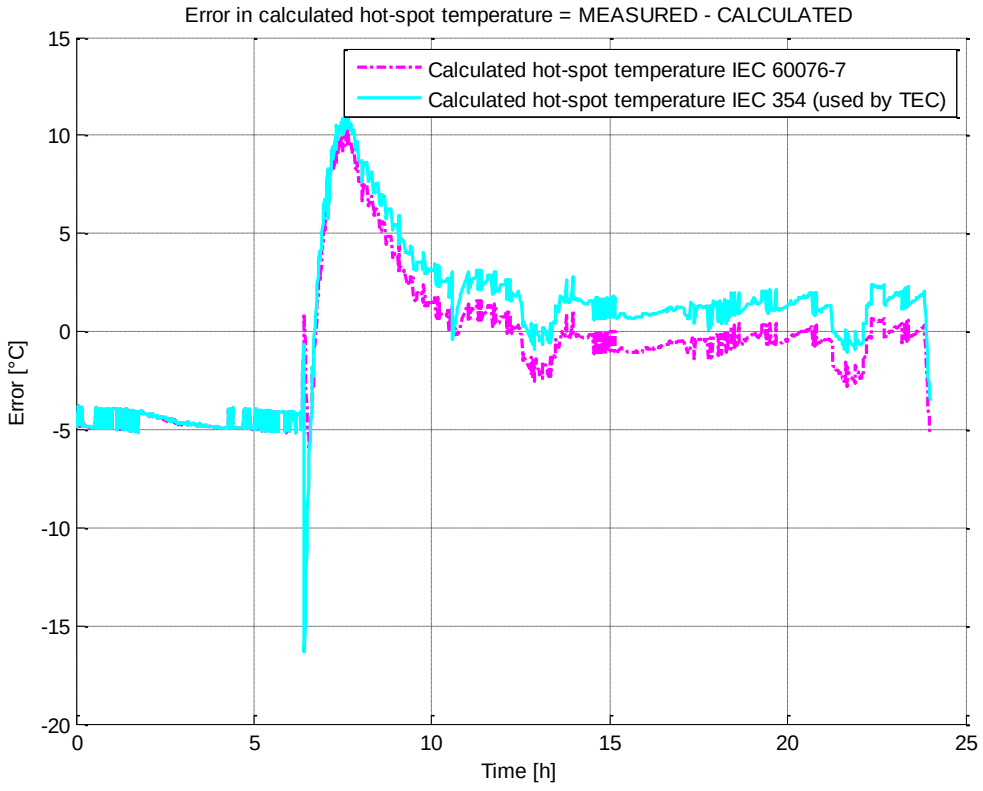

Fig. 10: The estimated error in calculated hot-spot temperature using Exponential method.

Fig. 10 shows the deviations between the measured and calculated hot-spot temperatures based on the measured top-oil temperature for both IEC 60076-7 and IEC 354.

4.2.2 Difference method during normal loading

The hot-spot temperature is calculated using the Difference equations method during a normal loading period. Fig. 11 shows a comparison of the measured hot-spot temperature using fibre optic sensors, with the calculated hot-spot temperature based on both measured and calculated top-oil temperatures.

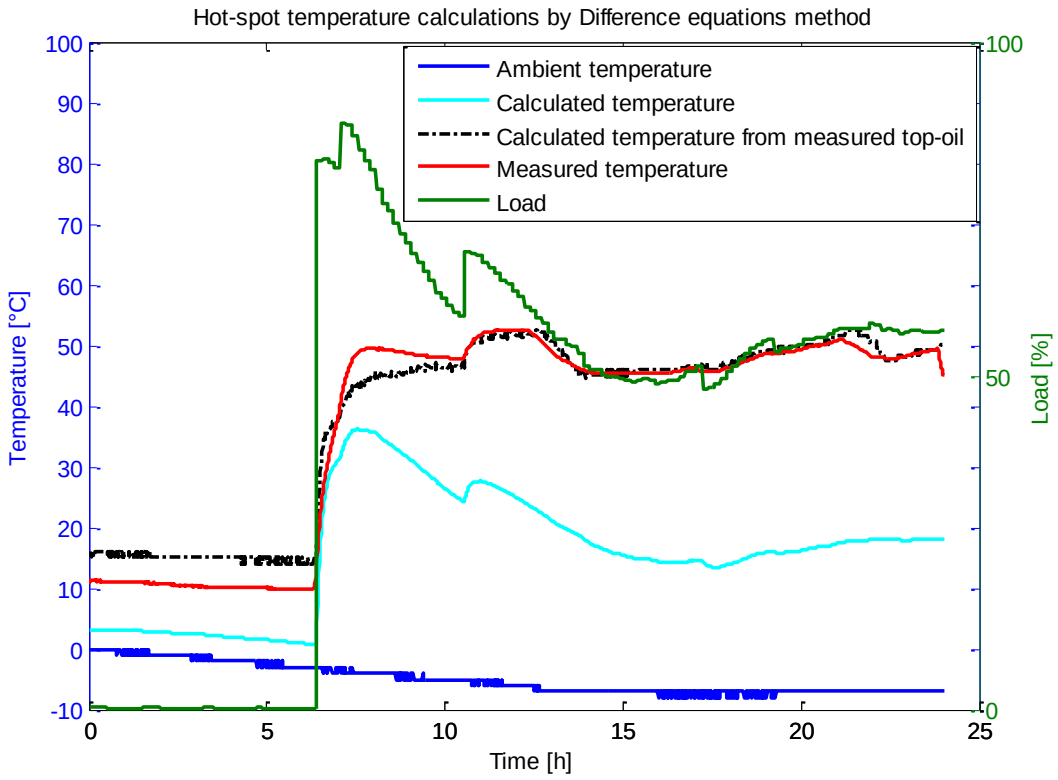

Fig. 11: Hot-spot temperature response calculated by Difference equations method during normal loading (the actual ambient temperature is a variable input to the model), Tr. 1.

The measurements show that the hot-spot temperature increases to 50℃ in about 1.5 h, when the load rises rapidly from almost zero to a peak value of 87% of the rated load.

The calculated hot-spot temperature based on the calculated top-oil temperature has an unacceptable response, as the calculated top-oil temperature is highly underestimated. With corresponding oil-time constant the value of this calculated hot-spot temperature is about 36℃ for which the measured value is 50 ℃.

The black curve is the calculated hot-spot temperature from the measured top-oil temperature in Fig. 11. The deviation between the measured and calculated hot-spot temperatures occurs during the rapid load increase as the calculated temperature is about 44℃ for which the measured value is 50 ℃.

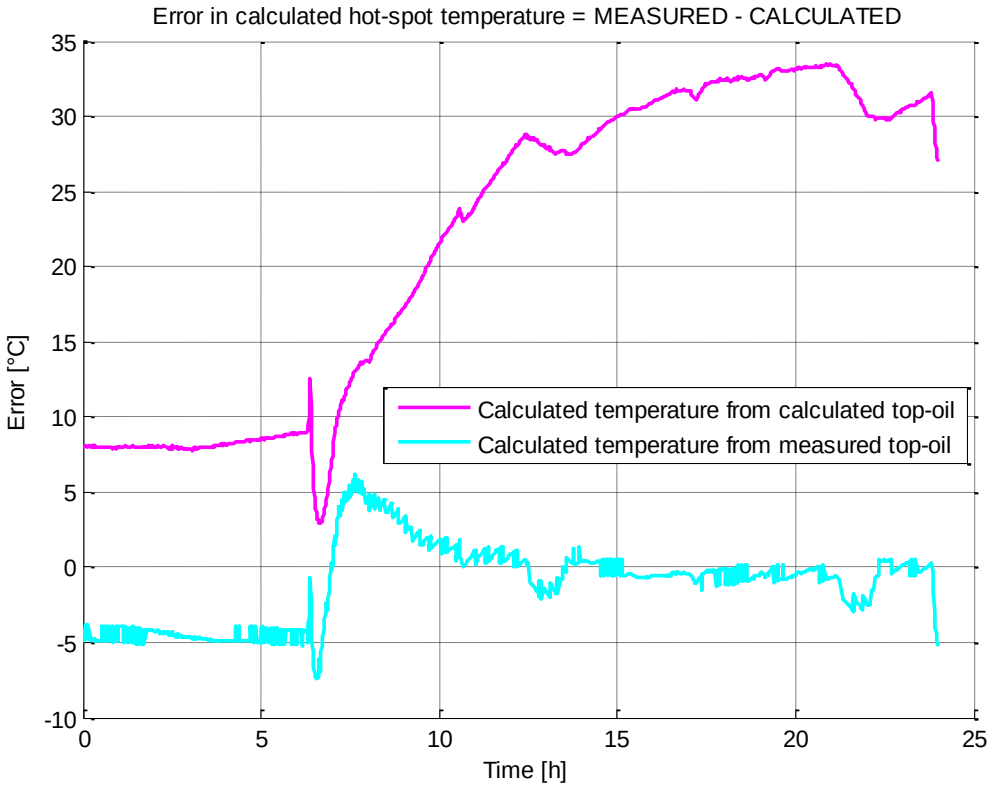

Fig. 12: The estimated error in the calculated hot-spot temperature using the Difference equations method (error which is lower than zero may be not so risky if it is not too high).

Fig. 12 shows the deviations between the measured and the calculated hot-spot temperatures based on both the calculated and measured top-oil temperatures.

4.2.3 Exponential method during over-loading

The hot-spot temperature is calculated using the Exponential equations method during an overloading period. Fig. 13 compares the measured hot-spot temperature using fibre optic sensors, with the calculated hot-spot temperatures using different approaches. There is a blind period in the hot-spot temperature measuring system, where the same value of hot-spot temperature is recorded for a certain period of time marked by a green ellipse in the figure.

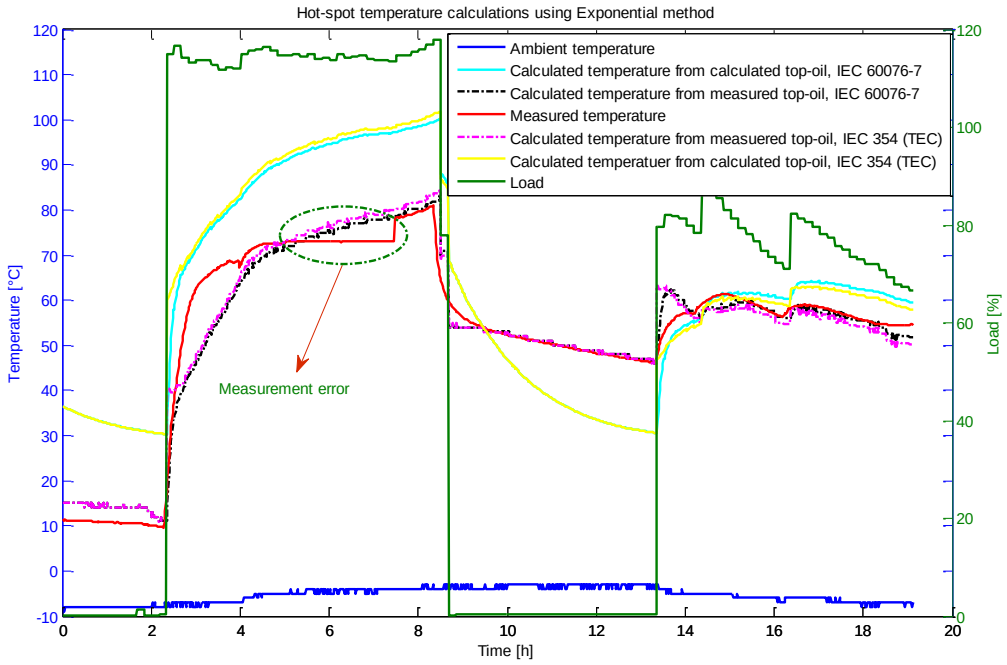

Fig. 13: Hot-spot temperature response calculated by Exponential method during overloading. The green ellipse indicates the duration in which measurement error occurred in the measuring system (a constant ambient temperature of 25℃ is used in the calculations), for Tr. 1.

There are deviations between the calculated hot-spot temperature and the measured hot-spot temperature. However, the calculated hot-spot temperature using measured top-oil temperature follows measured one, except during the rapid load increase. The calculated hot-spot temperature is lower than the measured hot-spot under a period of about 2 hours, starting from the time the load is almost zero to the time the load is 116% of the rated load.

On the other hand, during the second increasing load step, as the load arrives at about 80% of the rated; a higher temperature value is obtained during 1h.

The winding time constant is neglected in the Exponential method according to IEC 354, to produce the highest possible hot-spot temperature during load increase. This increase in the hot-spot temperature rise is slower for the Exponential method according to IEC 60076-7.

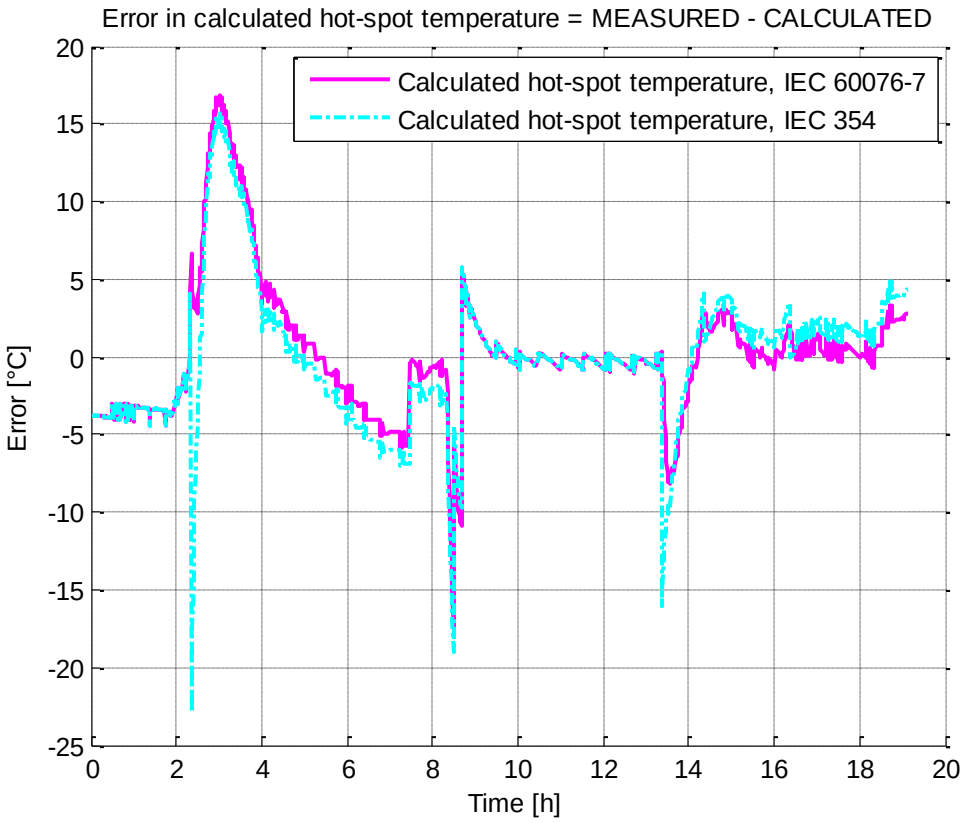

Fig. 14: Error estimation in calculated hot-spot temperature based on the measured top-oil temperature presented in the Fig. 13 (error which is lower than zero may be not so risky if it is not too high).

Fig. 14 shows the deviation between the measured and the calculated hot-spot temperatures based on the measured top-oil temperature for both versions of IEC.

4.2.4 Difference method during over-loading

Under overload situation the hot-spot temperature is calculated using the Difference equations method as it is stated in the IEC standard [2]. Fig. 15 shows the results of the temperature calculations plotted along with the measured temperature. The input variables to the model are the measured ambient temperature and the load every minute.

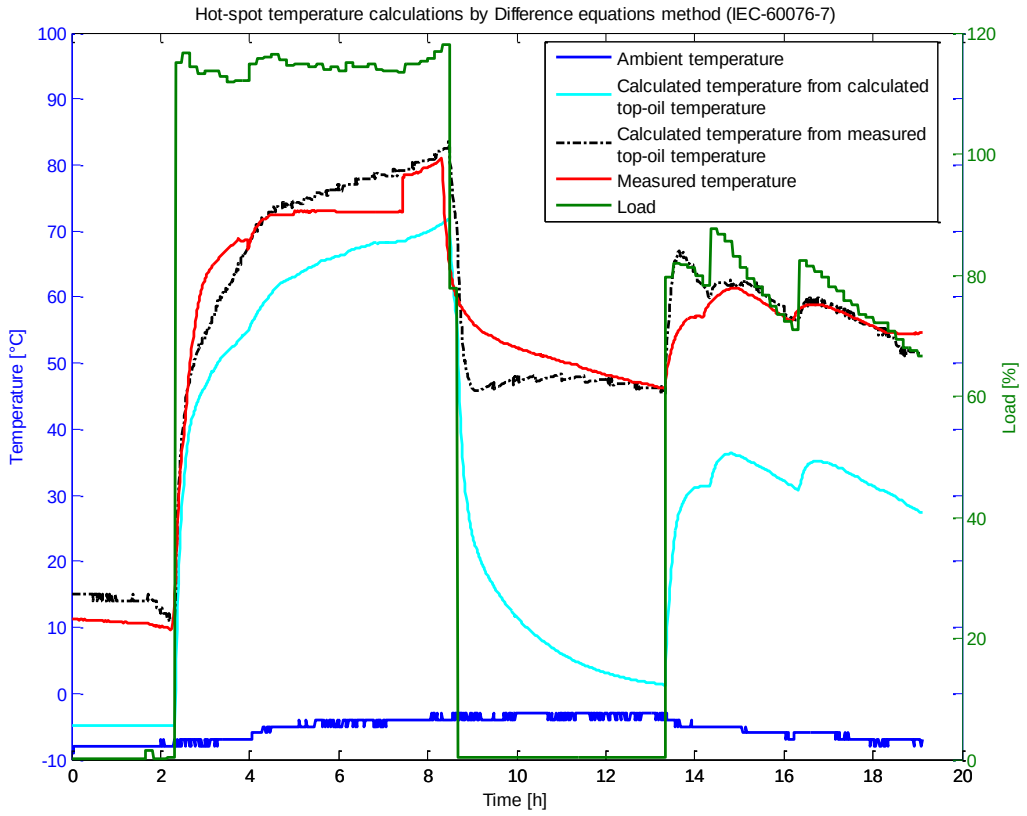

Fig. 15: The hot-spot temperature response calculated by the Difference equations method during overloading period, (the green ellipse indicates the duration in which measurement error occurred in the measuring system), for Tr. 1.

Fig. 15 shows the result of the hot-spot temperature calculation based on measured and calculated top-oil temperatures. The hot-spot temperature based on the calculated top-oil temperature gives low values both during increased load step and decreased load step.

However, the calculated hot-spot temperature based on the measured top-oil temperature agrees well with the measured hot-spot temperature except during the rapid load increase when the temperature is underestimated in time duration about 2 hours. On the other hand, the method underestimates the hot-spot temperature during a decreasing load step.

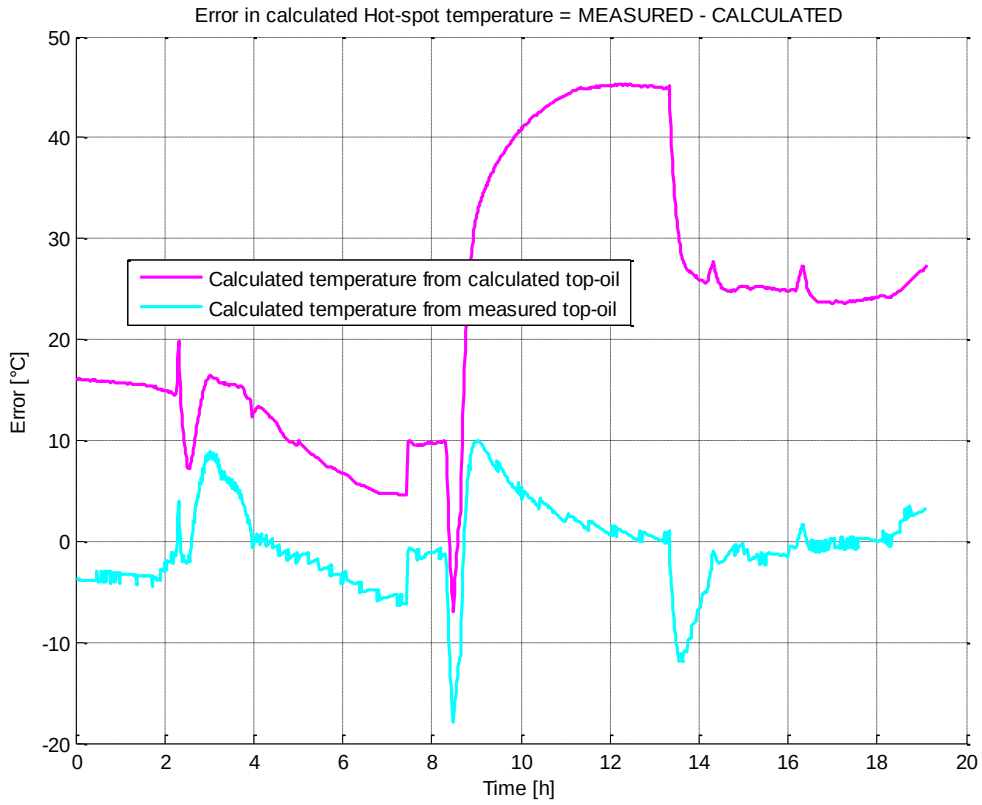

Fig. 16: Error estimation in calculated hot-spot temperatures by Difference equations method in Fig. 15 (error which is lower than zero may be not so risky if it is not too high).

Fig. 16 shows the deviations between the measured and the calculated hotspot temperatures based on both the calculated and the measured top-oil temperatures.

4.3 Loss of life calculations

The loss of life of the insulation paper has been calculated based on the measured hot-spot temperature for Tr. 1 under various load situations. The results are depicted in Fig. 17, 18 and 19.

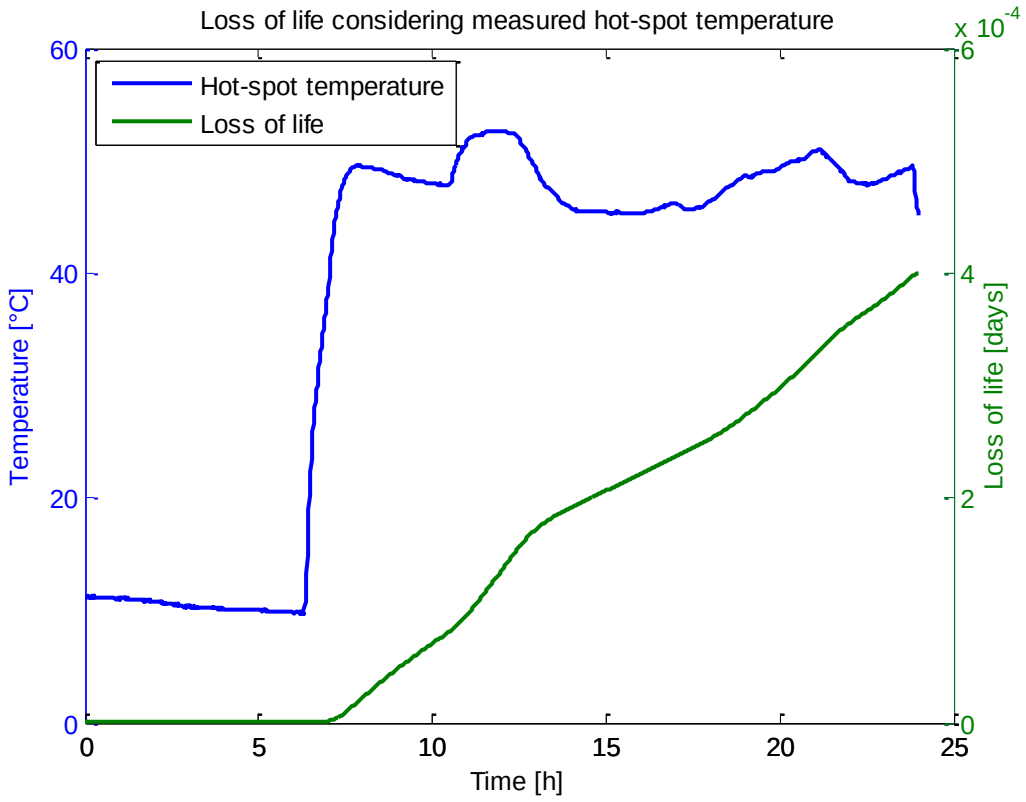

Fig. 17: The loss of insulation life, corresponding to the measured hot-spot temperature during a normal loading period, Tr. 1.

Fig. 17 shows the loss of insulation life corresponding the measured hot-spot temperature for Tr. 1 during a normal loading period. The maximum hot-spot is about 50 ℃ and the accumulated loss of life in the end of the period is about 0.0004 days which is equivalent to 0.6 minutes.

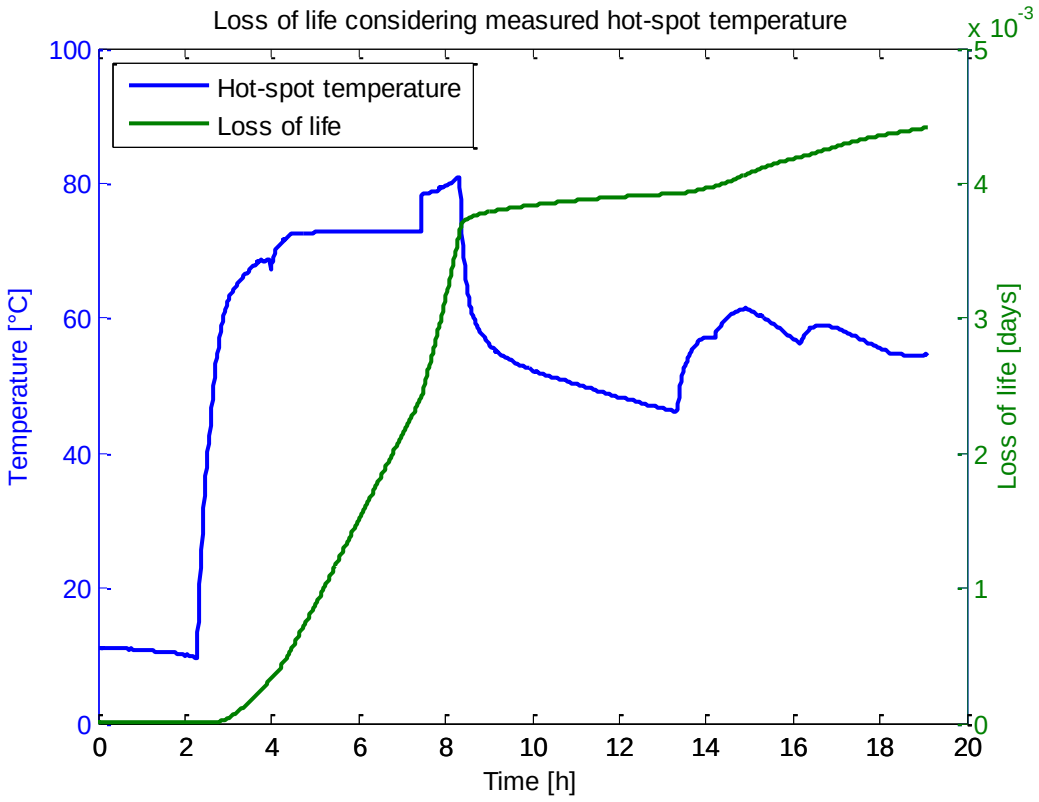

Fig. 18: Loss of insulation life, corresponding to the measured hot-spot temperature during an overloading period, Tr. 1.

Fig. 18 shows the result of loss of life of insulation calculations during an overloading period considering the measured hot-spot temperature. The maximum hot-spot temperature is about 80°C and the accumulated value for loss of life is about 0.0044 days which is equivalent to 6.64 minutes; higher than that obtained during normal loading in Fig. 17.

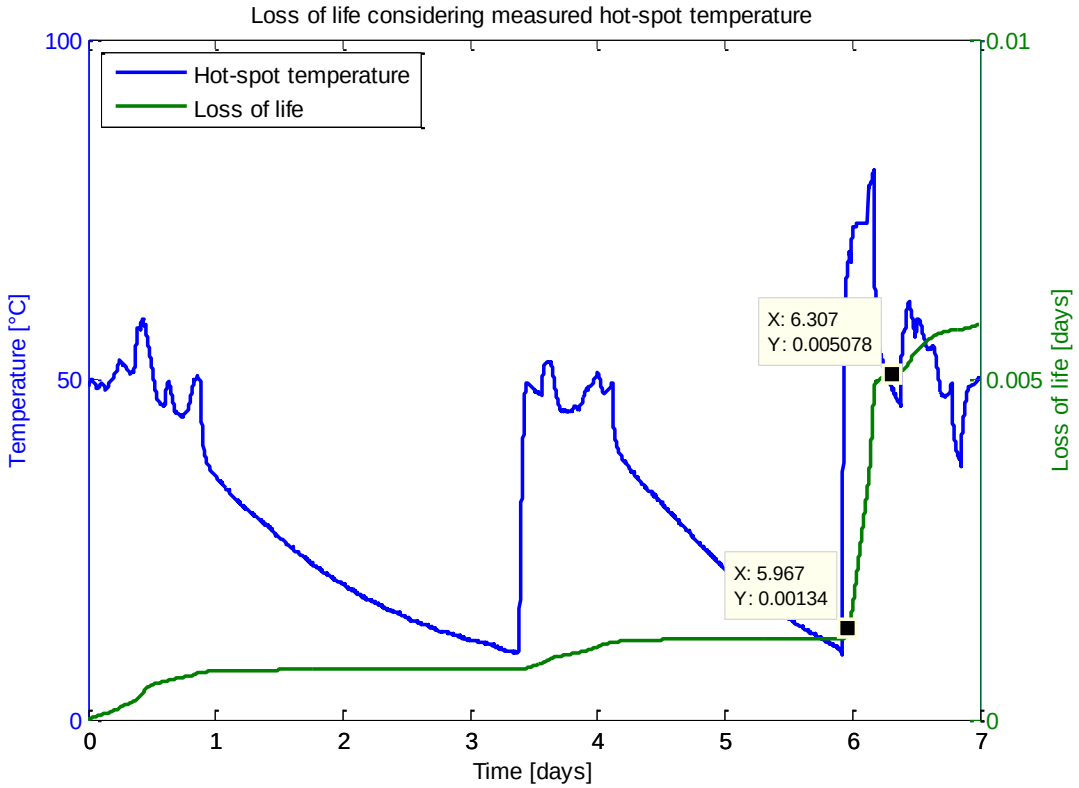

Fig. 19: The calculated loss of life during a seven days loading period, Tr. 1.

Fig. 19 shows the accumulated loss of life after a seven days loading period which has a value of 0.0057 days, which is equivalent to 8.2 minutes. It shows also that the loss of life is increasing rapidly from 2 minutes to 7 minutes, during a rapid rise of the hot-spot temperature from 10℃ to 80℃.

5 Model Deviations and Discussion

A transformer can be seen as a three-mass composite body; winding, core and oil. The temperature in any part of the body rises when the heat content increases, and consequently heat transfer among these three parts. The heat transfer characteristics among these parts are complex phenomena which can be simplified by using a proper thermal model. Compromise between simplicity and accuracy is often a factor in developing these thermal models.

However, direct heat transfer between winding and core is often neglected in models as insulating cylinders are placed between them [9]. Thus, in practical calculations, the transformer is considered as a body with decreasing and increasing temperature, following the exponential law. These simplifications, eventually lead to deviations between calculated and measured hot-spot temperature values.

The exponential method is more applicable for decreasing and increasing type step loads considering the fact that the temperature reaches steady state after each variation. However, the loading described in this text was not a pure step function and so is in practice, but rather a dynamic load under normal operation. Thus, the hot-spot temperature response for the dynamic load variation will not be as accurate as the case for step like load variations.

The result of the calculation of the top-oil temperature indicates that the model is inapplicable during very low temperatures, using the actual ambient temperatures as the input variable to the model. According to [12], the viscosity of the oil affects the results in very cold weather, while during nominal temperature of around 30℃ the viscosity has almost a negligible effect.

According to IEEE [1], the duct oil temperature may be unusually higher than the top-oil in the tank during overloading conditions. The temperature in the cooling ducts rises faster than the top-oil temperature in the tank [30]. When calculating the hot-spot temperature, it is assumed that the temperature in the cooling ducts is the same as the top-oil temperature in the tank. Thus, underestimation of the hot-spot temperature may occur as calculations are based on the top-oil temperature in the tank.

The IEC 354 standard states: "*As the time constant of windings is usually very short (5 min to 10 min), it has only a limited effect on the hot-spot temperature, even under short loads of high values. Since the shortest peak load duration considered in the loading tables is 30 min (section 3), the time constant is taken as equal to zero in the calculation*" [24].

Thus, in the old version of the IEC, i.e. IEC 354, the winding time constant is neglected to calculate the highest possible hot-spot temperature. The IEC model produces a lower value of hot-spot temperature using only winding time constant [30]. However, the underestimation of hot-spot temperature will be less pronounced during a non-ONAN cooling modes [30], wherein the time lag between the top-oil temperature rise and the oil temperature rise in the winding cooling ducts is diminished.

However, in the new version of IEC standard [2], the winding time constant is taken into account when calculating the hot-spot temperature rise during load increase. The exponential function f_2 represents the influence of the winding time-constant, described in section 3.4.2. Moreover, the oil time-constant besides the winding time-constant is included in the function f_2.

The results of the hot-spot temperature calculations show that the response of the Difference equations method is better than the Exponential method. To analyse the Difference equations method, simulations are performed using various cooling modes of the transformer.

Standards cooling methods of power transformers can be identified according to table 7 [1], [2]. The first two letters stands for internal cooling and the last two letters for external cooling. The first and the third letters represent cooling medium, and the second and the last letters stand for cooling mechanism.

Table 7: Transformer cooling types.

Cooling classes	Description
ONAN	Oil natural air natural, without pump and fans
ONAF	Oil natural air forced, without pump for oil, with fans for air
OFAF	Oil forced air forced, with pump for oil and fans for air
OFAN	Oil forced air natural, with pump for oil
OD	Directed oil flow

Fig. 20 illustrates three examples of power transformer cooling types [32].

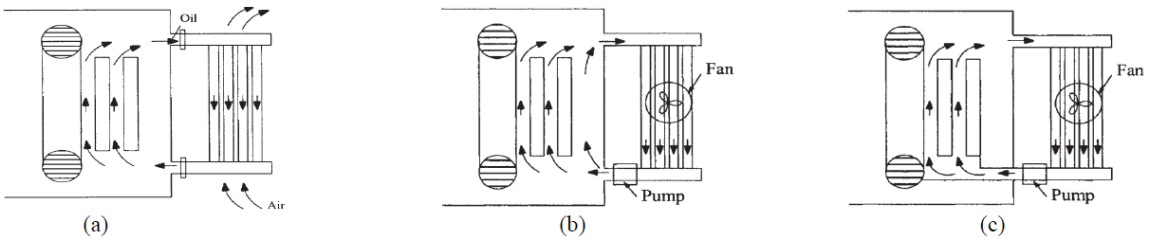

Fig. 20: Three types of cooling for power transformers: (a) ONAN, (b) OFAF, and (c) ODAF.

ONAN means that the oil circulates naturally through the windings and the cooling equipment, which is externally cooled by natural air flow. ONAF means that the oil circulates naturally through the windings and cooling equipment but air is forced to the surface of the radiators. In an OFAF type, the rate of the heat transfer is increased by forcing the oil circulation with pumps, and fans are used to blow air on the surface of the radiators. OD means that the oil is directed to flow through the windings, and when fans are used in the external cooling equipment, it becomes ODAF.

A number of simulations are performed so as to calculate the hot-spot temperature using the Difference equations method with different cooling modes. The results are presented in the following sections.

5.1 Oil natural –to– oil forced mode

As an undesirable underestimation of the hot-spot temperature often occurs during a rapid load increase, it is suspected that the actual internal cooling state is not correctly accounted for in the model. Thus, the internal cooling variation has been included in the model. In order to detect the status of the internal cooling during the operation, the oil flow measurement from the oil pump can be used as an indicator for the variation of the cooling mode. This means that the Tr. 1 can sometimes operate as an ONAF cooling unit although it is designated as OFAF on the rating plate; hence the hot-spot temperature is calculated by taking the internal cooling variation in the transformer into account.

The measured and the calculated hot-spot temperature, the load and the measured top-oil temperature are depicted in Fig. 21 for a normal loading period and Fig. 22 for an overloading period.

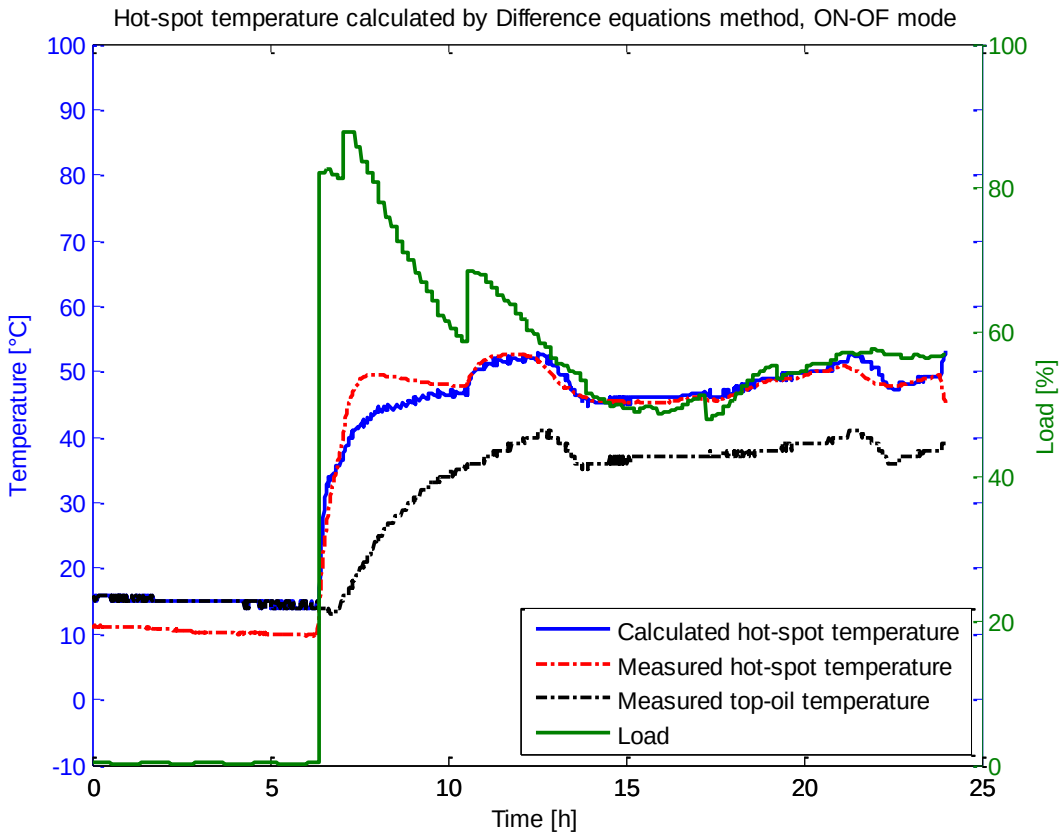

Fig. 21: The calculated hot-spot temperature using Difference equations method during a normal loading period for Tr.1. The actual mode of the internal cooling of the transformer is considered in the model, thus for sometimes the transformer is ON and for sometimes OF.

Fig. 21 shows the deviation between measured and calculated hot-spot temperature during load increase as the hot-spot temperature is underestimated. Thus, it seems that the forced oil circulation in the windings is not as effective as it should be during peak load and the forced oil flow using an oil pump may not cool down the hot-spot as required. One explanation for this phenomenon may be because of the decreasing oil velocity in the cooling ducts due to an increased hydraulic resistance which leads to reducing oil mass and heat transfer through the windings [31].

In addition, it may take time for the oil flow through the windings to get adapted to its speed of circulation and dissipate the heat at a rate belonged to OFAF mode when the pump is turned on. Thus, there is a time lag between the cooling modes when the pump is turned on and off, i.e. at the instant the pump is turned on, it is not sure that the actual cooling mode is also changed. However, this phenomenon may include in the model.

Furthermore, Fig. 21 shows that the measured top-oil temperature is higher than the measured hot-spot temperature during the period when the load is almost zero. The hot-spot temperature is modelled as the sum of the top-oil temperature and the hot-spot temperature rise above top-oil. According to the measurement the hot-spot temperature rise is negative during the period which may not be realistic. However, the reason for higher top-oil temperature, compared to the hot-spot temperature, can be either an error in the measurement or the time was not enough for the heat of the oil to dissipate. One can also realise that the transformer had been very cold before the measurements started. However, before the period considered in Fig. 21, the transformer had been loaded as can be seen later in Fig. 43.

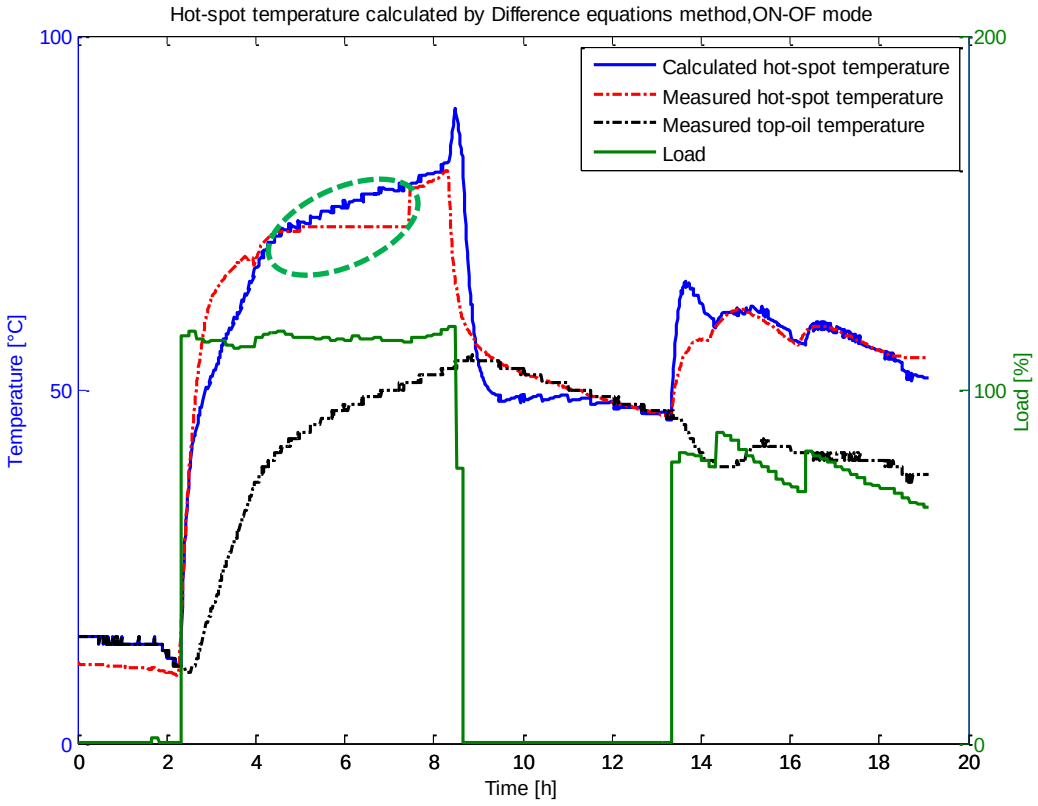

Fig. 22: The calculated hot-spot temperature using Difference equations method during an overloading period, Tr.1. The actual mode of the internal cooling of the transformer is considered every minute in the model, thus sometime the transformer is ON and sometime OF. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 22 compares the calculated hot-spot temperature with the measured hot-spot temperature during an overloading period. The hot-spot temperature is underestimated under both load increase and decrease. However, the model is better during load decrease.

In addition, there is a spike in the hot-spot temperature just as the load decreases at about 8.5 hour, because the internal cooling mode is set to oil natural ON in the model at that instant. Thus, the model produces a higher value of hot-spot temperature.

In addition, there is a blind period in the hot-spot temperature measuring system marked by a green ellipse in about (3.8 h) during overloading, exactly between (3.7h - 7.5h) which can be disregarded in the comparisons.

5.2 Oil natural –to– oil forced restricted mode

The oil circulation can be restricted if the winding of an ON or OF-cooled transformer is zigzag-cooled and the thickness of a radial spacer is less than 3 mm [2]. With the same cooling mode as in the section 5.1.1 but considering restricted oil circulation, the hot-spot temperature is calculated. Fig. 23 compares the calculated hot-spot temperature with the measured hot-spot temperature during a normal loading period and Fig. 24 during an overloading period.

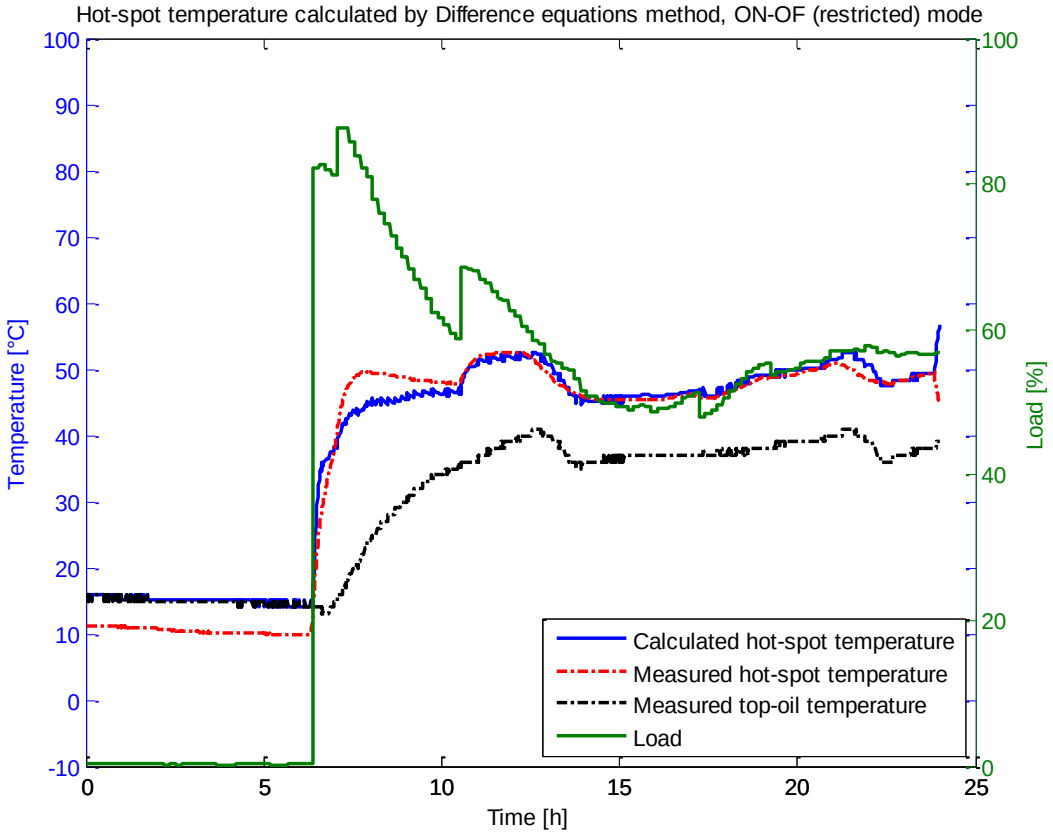

Fig. 23: The calculated hot-spot temperature using Difference equations method during a normal loading period, Tr. 1. The actual mode of the internal cooling of the transformer is considered every minute in the model, thus sometime the transformer is ON and sometime OF with restricted oil circulation.

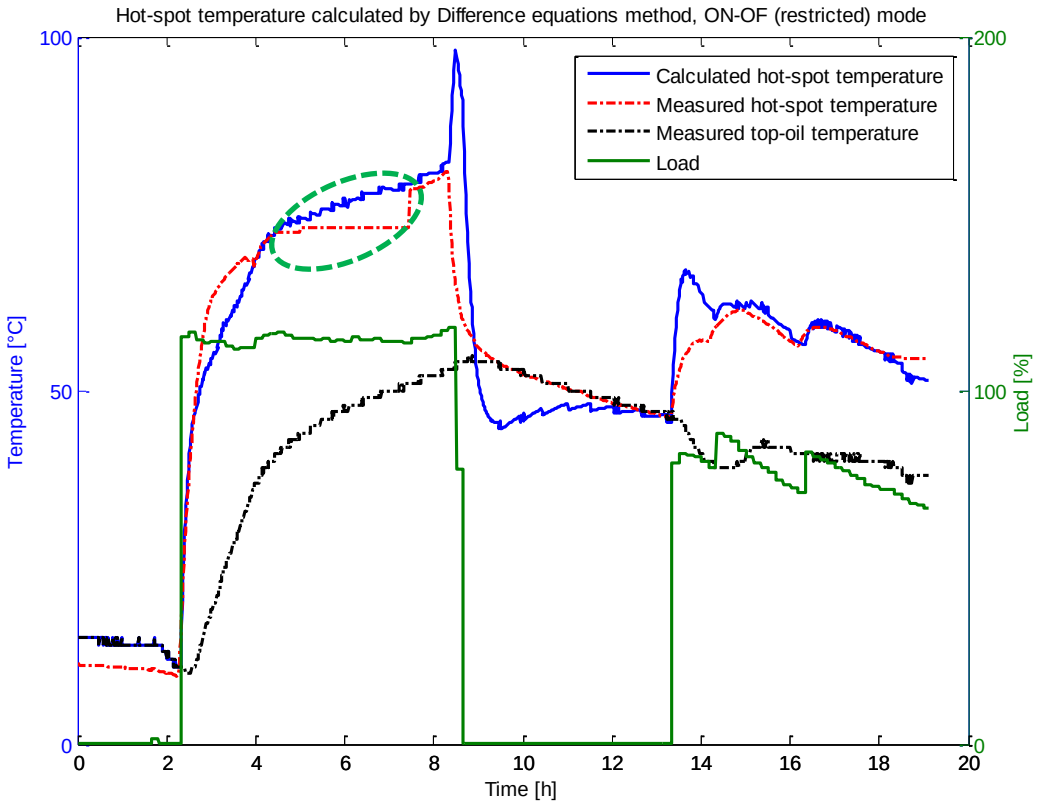

Fig. 24: The calculated hot-spot temperature using Difference equations method during an overloading period, Tr. 1. The actual mode of the internal cooling of the transformer is considered every minute in the model, thus sometime the transformer is ON and sometime OF with restricted oil circulation. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 23 and 24 show that the model still underestimates the hot-spot temperature during load increase even if the restricted oil circulation is considered in the model.

In addition, there is also a spike in the hot-spot temperature just as the load decreases at about 8.5 hour producing even a higher value of hot-spot temperature than the previous case shown in Fig. 22.

It seems that, the deviation occurs at the time the internal cooling mode is changed in the calculation. The model assumes that the internal cooling in the transformer is changed directly when the pump is turned on or turned off which can be not realistic. Simulations were performed by increasing the time for switching the internal cooling mode between ON and OF in the transformer. However, the result of the simulations was still unsatisfied.

5.3 Oil forced air forced mode

The transformer cooling class is OFAF according to its rating plate. The hot-spot temperature is calculated considering the OFAF cooling mode. The calculated hot-spot temperature is depicted in Fig. 25 during a normal loading period and Fig. 26 during overloading period.

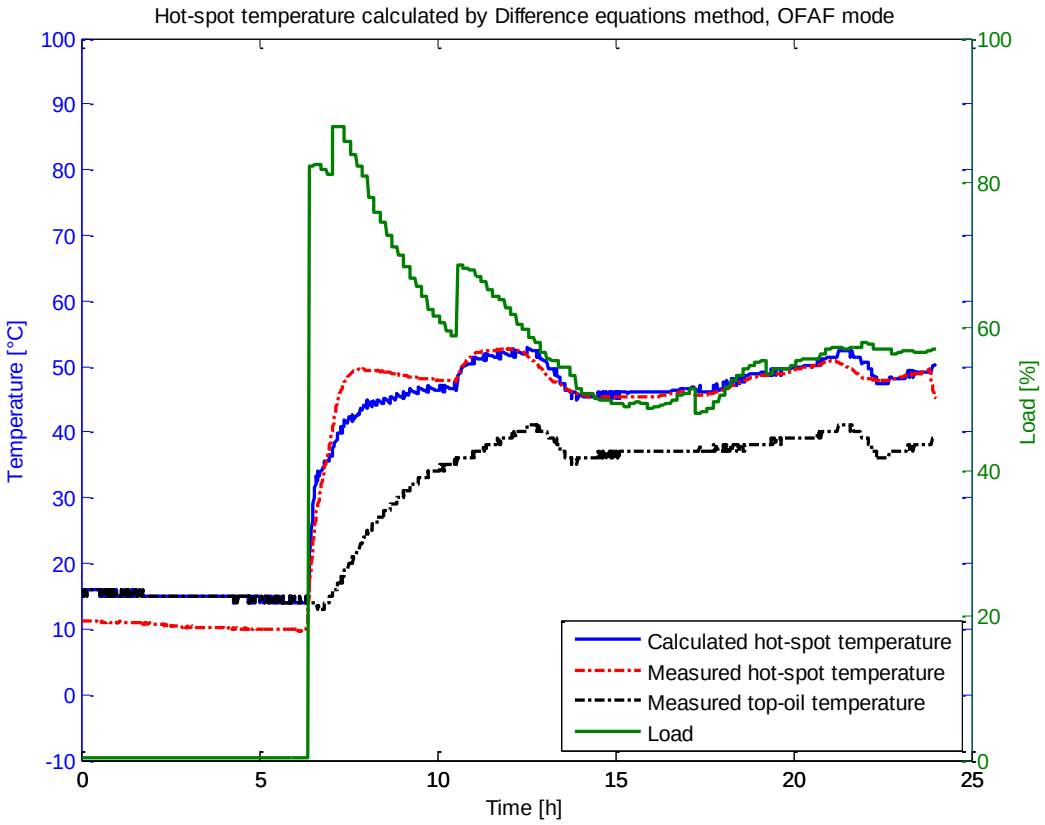

Fig. 25: The calculated hot-spot temperature using Difference equations method during a normal loading period, Tr. 1. The cooling is set according to its nameplate that is OFAF.

Fig. 25 shows that the Difference equations method with OFAF cooling mode underestimates the hot-spot temperature during load increase.

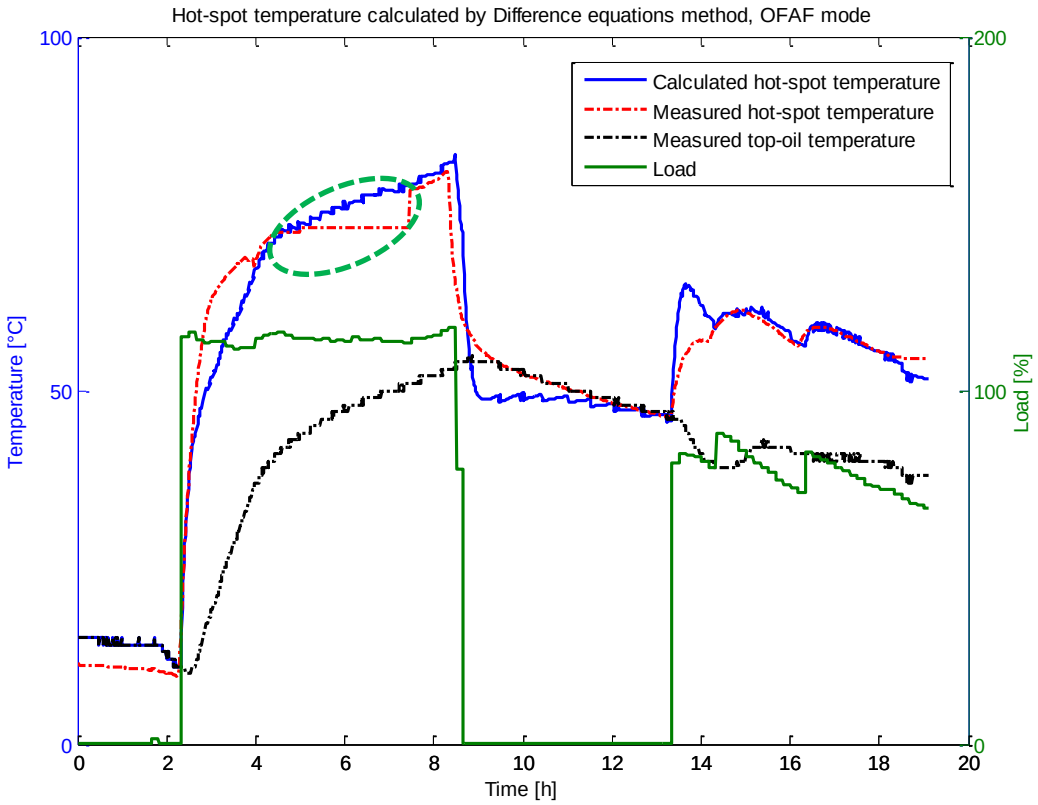

Fig. 26: The calculated hot-spot temperature using Difference equations method during an overloading period, Tr. 1. The cooling is set according to its name plate that is OFAF. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 26 shows that, the Difference equations method with OFAF cooling mode underestimates the hot-spot temperature during load increase at the time duration between (2.5 – 4.5) hours, and overestimates the hot-spot temperature between (13.5 – 14) hours.

5.4 Oil forced air forced restricted mode

The transformer cooling class is OFAF according to its nameplate rating and it is assumed that the oil circulation through the windings is restricted. The result of the calculated hot-spot temperature is depicted in Fig. 27 during a normal loading period and Fig. 28 during an overloading period.

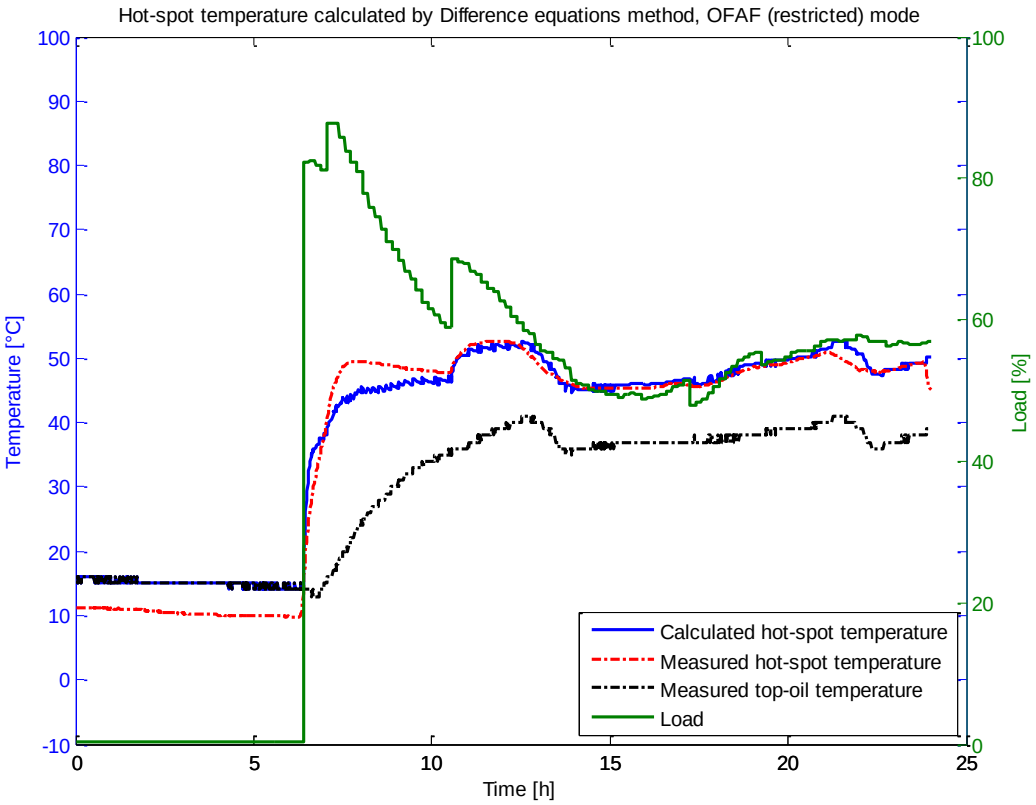

Fig. 27: The calculated hot-spot temperature using Difference equations method during a normal loading period, Tr. 1. The cooling is set according to its name plate, that is OFAF, but it is assumed that the oil circulation is restricted.

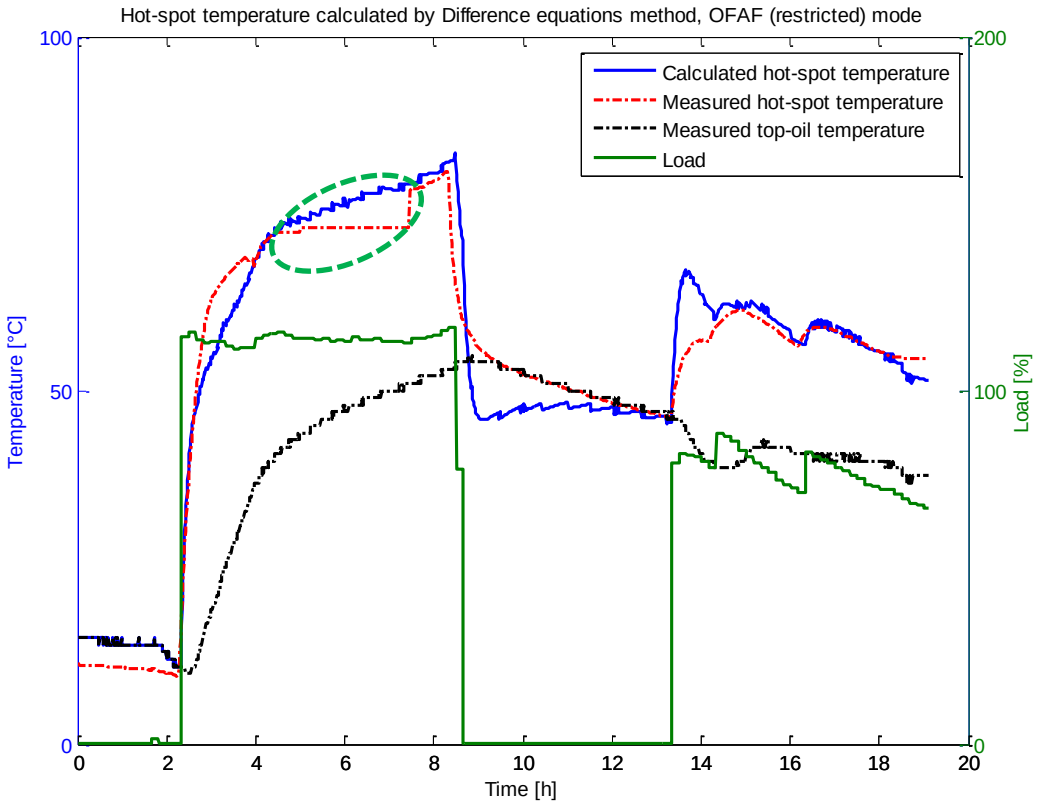

Fig. 28: The calculated hot-spot temperature using Difference equations method during an overloading period, cooling is set according to its name plate, that is OFAF, but it is assumed that the oil circulation is restricted. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 27 and 28 show that, the calculated hot-spot temperature using the Difference equations method with OFAF restricted mode does not agree with the measured value.

5.5 Oil natural air forced mode

The hot-spot temperature is calculated considering the ONAF cooling mode in the model. The curves of calculated and measured hot-spot temperatures along with the measured top-oil temperature are depicted in the Fig. 29 for a normal loading period and Fig. 30 for an overloading period.

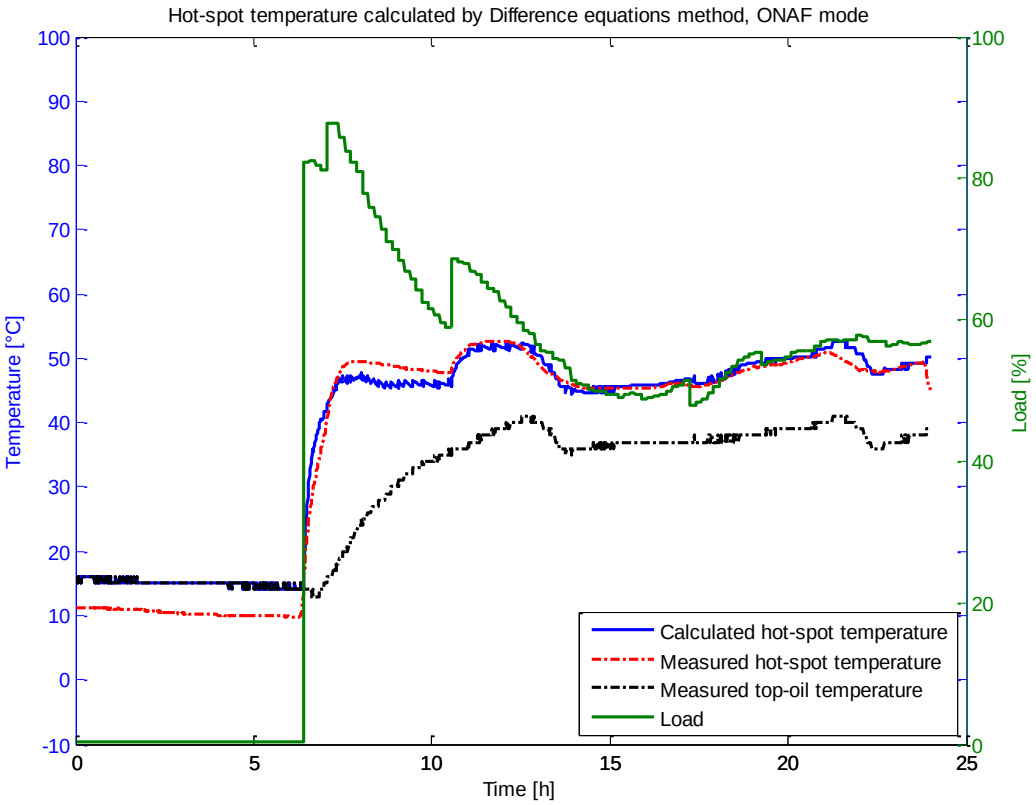

Fig. 29: The calculated hot-spot temperature using Difference equations method during a normal loading period, Tr. 1. The cooling mode is assumed to be ONAF.

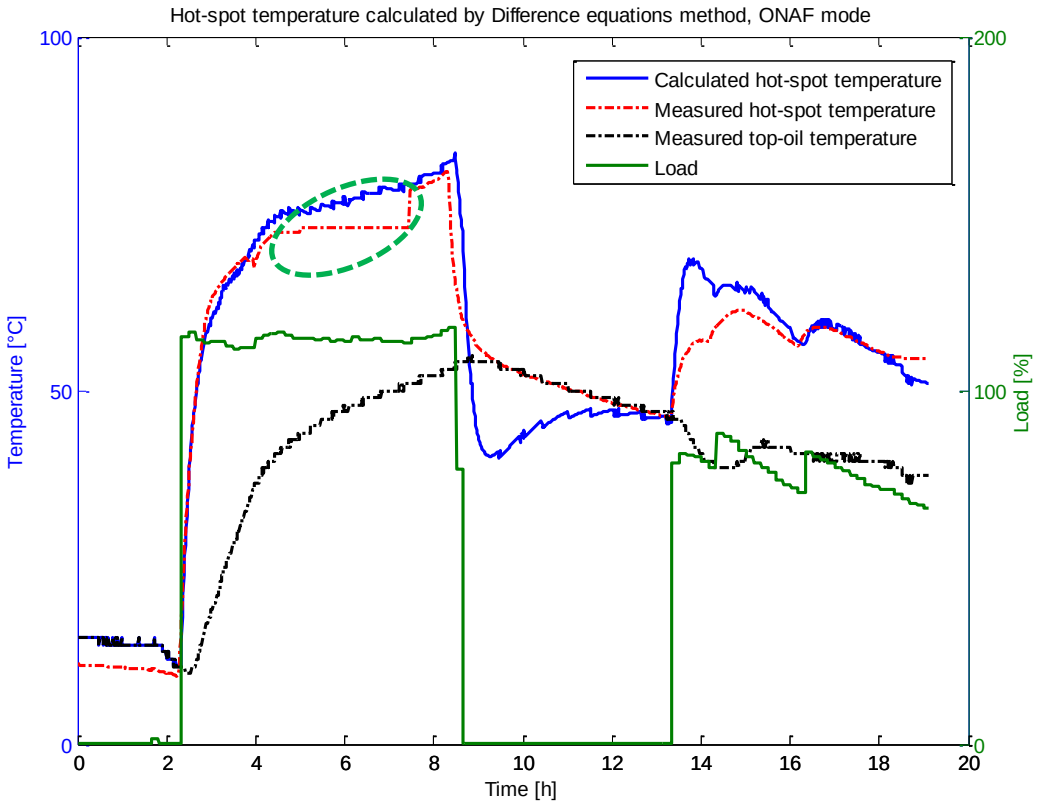

Fig. 30: The calculated hot-spot temperature using Difference equations method during an overloading period, Tr. 1. The cooling mode is assumed to be ONAF. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

It is shown in Fig. 29 and 30 that an improvement in the result of hot-spot temperature calculation is obtained considering the ONAF cooling mode in the model.

5.6 Oil natural air forced restricted mode

Same as in section 5.5 but it is assumed that the oil circulation is restricted. The curves of calculated and measured hot-spot temperature along with the measured top-oil temperature and the load are depicted in the Fig. 31 and 32.

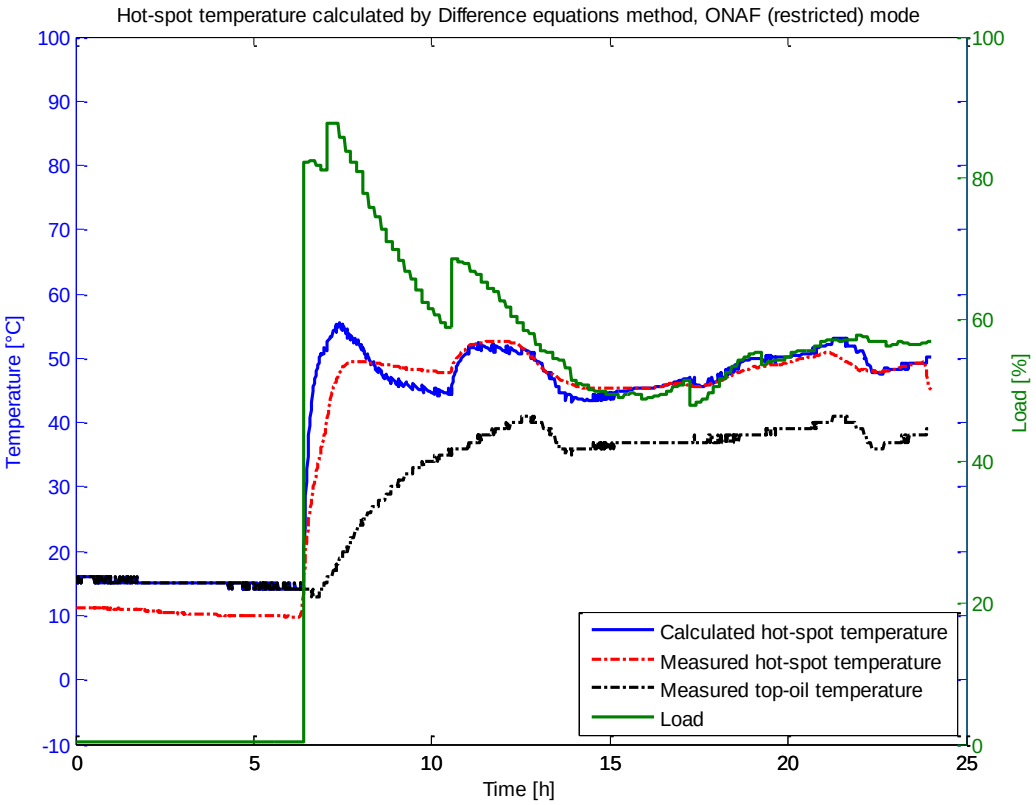

Fig. 31: The calculated hot-spot temperature using Difference equations method during a normal loading period, Tr. 1. The cooling mode is assumed to be ONAF restricted.

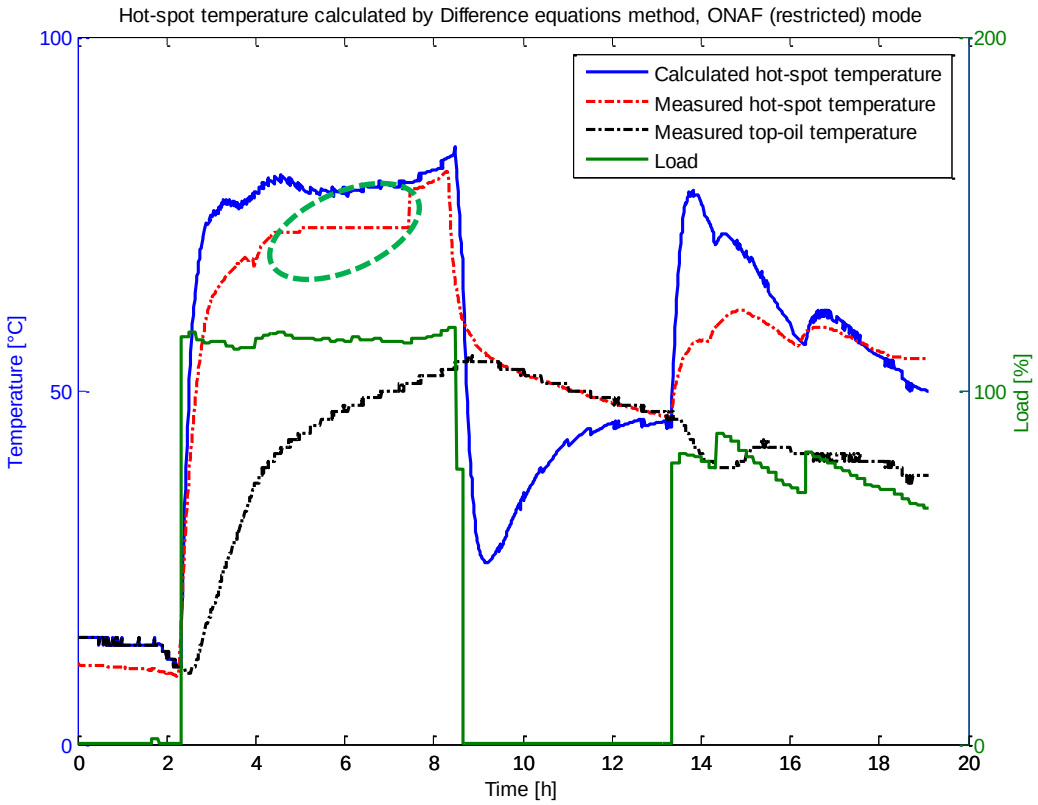

Fig. 32: The calculated hot-spot temperature using Difference equations method during an overloading period, Tr. 1. The cooling mode is ONAF restricted. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 31 and 32 show that, the calculated hot-spot temperature using the Difference equations method with ONAF restricted mode does not agree with the measured value. The hot-spot temperature is overestimated during load increase.

5.7 Oil natural air natural – mode

The hot-spot temperature is calculated considering the ONAN cooling mode in the model though the transformer rating plate says OFAF. The curves of the calculated and the measured hot-spot temperatures along with the measured top-oil temperature and the load are depicted in the Fig. 33 for a normal loading period and Fig. 35 for an overloading period.

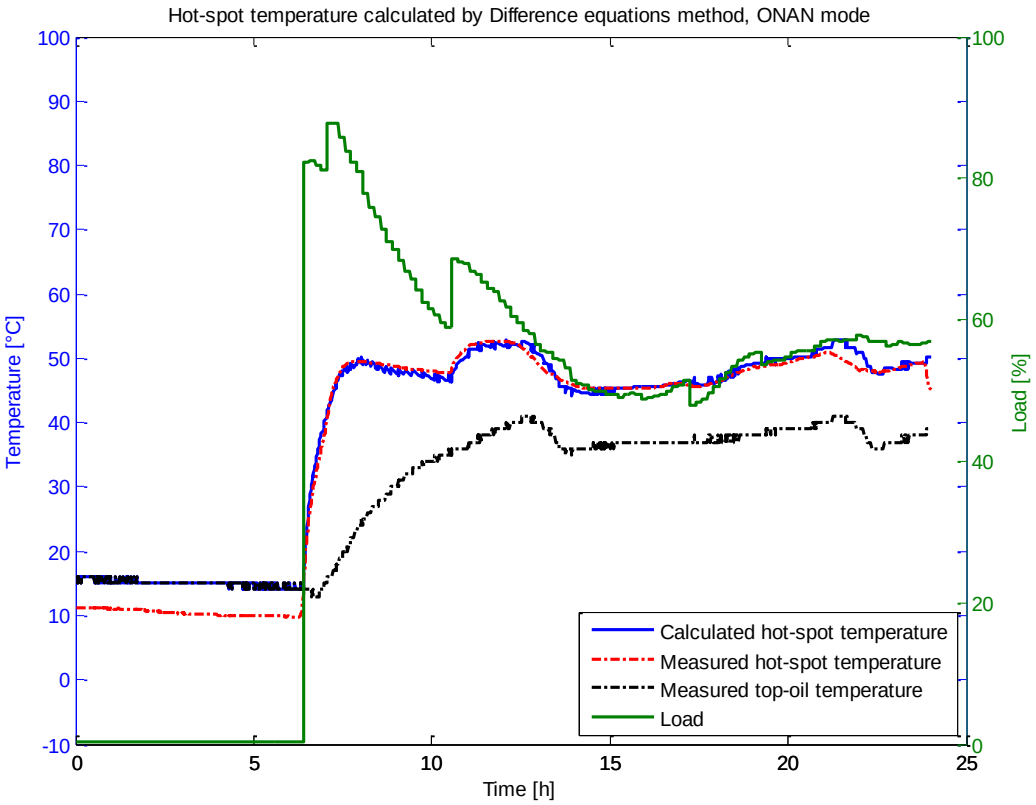

Fig. 33: The calculated hot-spot temperature using the Difference equations method during a normal loading period, Tr. 1. The cooling mode is assumed to be ONAN.

As it is shown in Fig. 33, a significant improvement of the calculated hot-spot temperature for Tr. 1 can be achieved by considering ONAN cooling class as the cooling type of the transformer. The calculated hot-spot temperature agrees well with the measured hot-spot temperature compared to the previous calculations based on the other cooling modes. It seems that the transformer operates as an ONAN unit during the rapid load increase although it is an OFAF. This could be an indication for reduced cooling efficiency during the overloading.

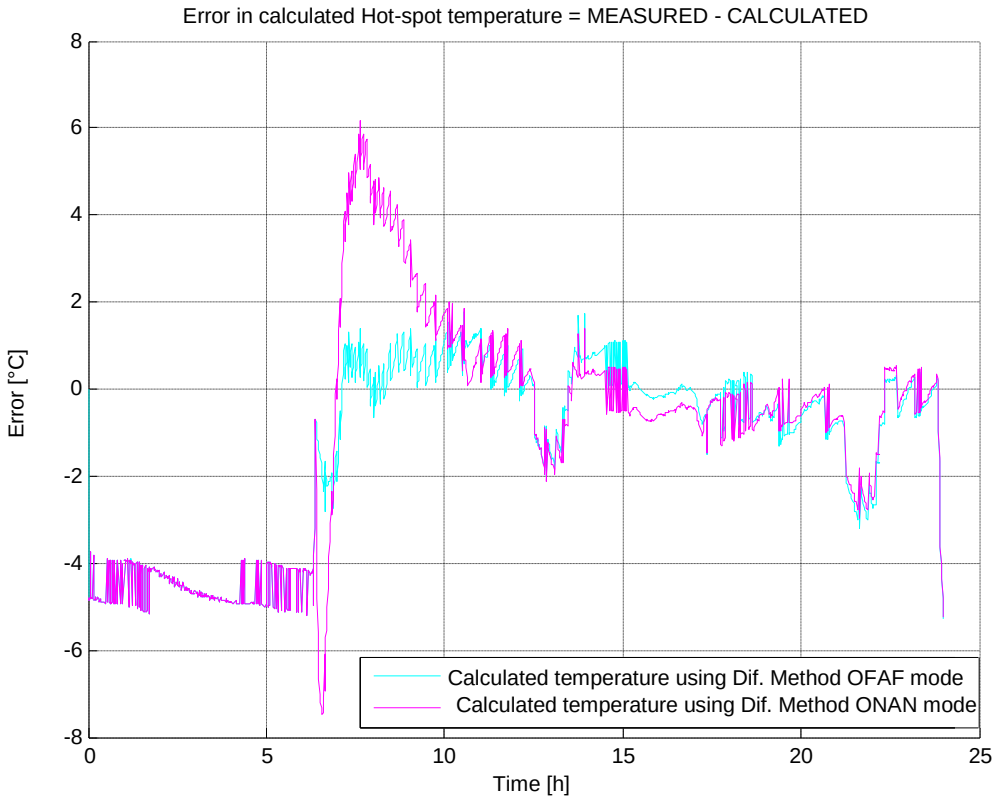

Fig. 34: The deviation between the calculated and the measured hot-spot temperature for both OFAF and ONAN mode during a normal loading period, Tr. 1.

Fig. 34 shows the deviation between measured and calculated hot-spot temperature using the Difference equations method with ONAN and OFAF cooling mode during a normal loading period. The reduction of error can be observed using the Difference equations method with ONAN cooling mode, which is about 5 degrees.

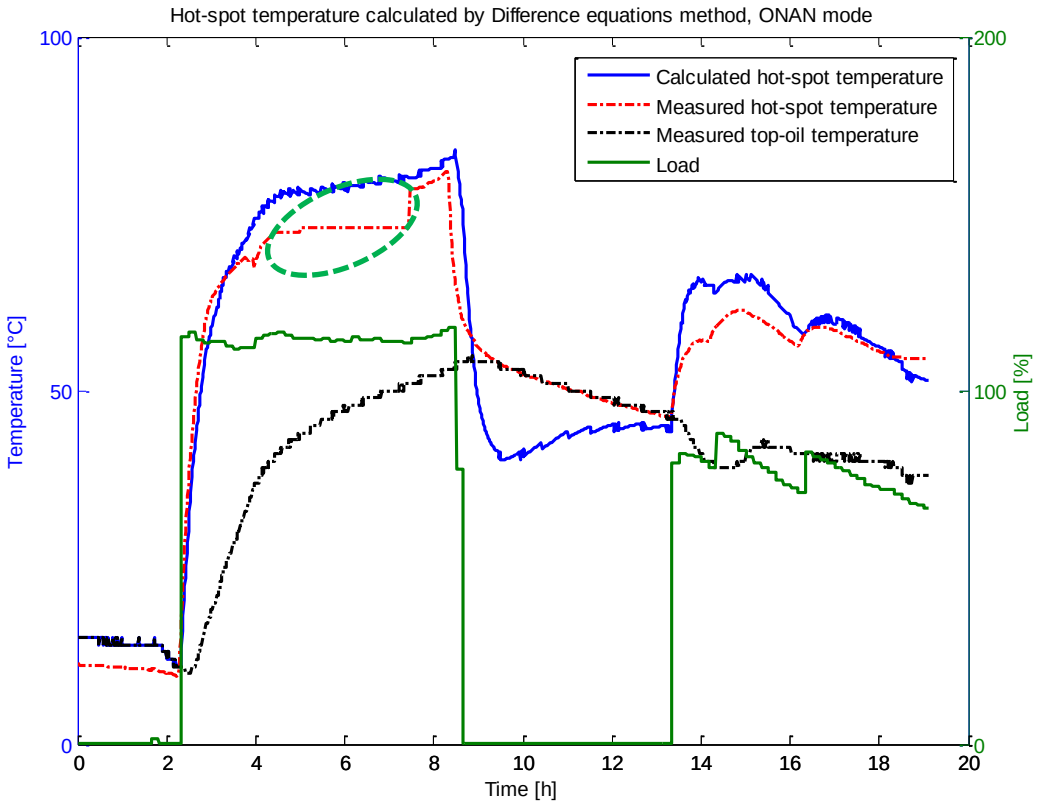

Fig. 35: The calculated hot-spot temperature using the Difference equations method during an overloading period, Tr. 1. The cooling mode is assumed to be ONAN. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 35 depicts a comparison of the measured hot-spot temperature the calculated hot-spot temperature using the Difference equations method with ONAN cooling mode during an overloading period. The reduction of the deviation comparing to other cooling modes can be observed during load increase.

The temperature is underestimated during load decrease which is probably an effect of overestimating the time constant of the cooling. For practical applications, it is however not a critical case for transformers, as the system has no risk of overheating.

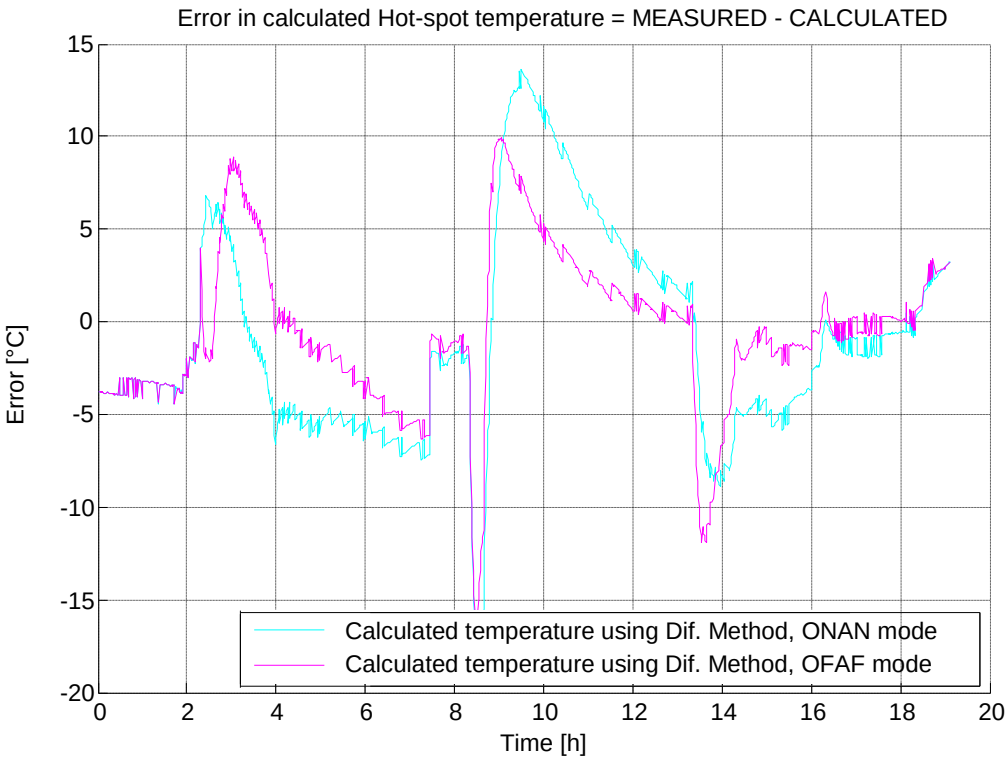

Fig. 36: The deviation between the calculated and the measured hot-spot temperatures for both OFAF and ONAN mode during an overloading period, Tr. 1.

Fig. 36 shows the deviation between measured and calculated hot-spot temperatures using the Difference equations method with ONAN and OFAF cooling mode during an overloading period. The reduction of error can be observed using the Difference equations method with ONAN cooling mode.

5.8 Oil natural air natural restricted mode

This is the same model as described in section 5.7 but it is assumed that the oil circulation through the windings is restricted. The curves of the calculated and the measured hot-spot temperatures along with the measured top-oil temperature and the load are depicted in the Fig. 37 for a normal loading period and Fig. 38 for an overloading period

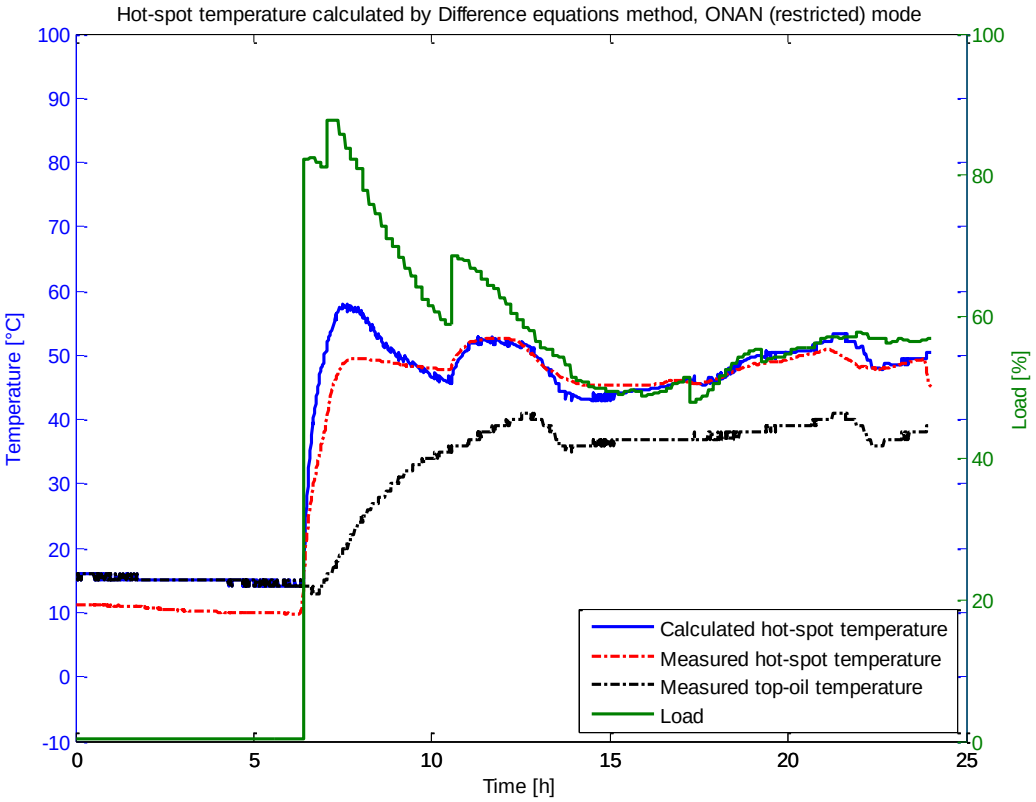

Fig. 37: The calculated hot-spot temperature using the Difference equations method during a normal loading period, Tr. 1. The cooling mode is assumed to be ONAN restricted mode.

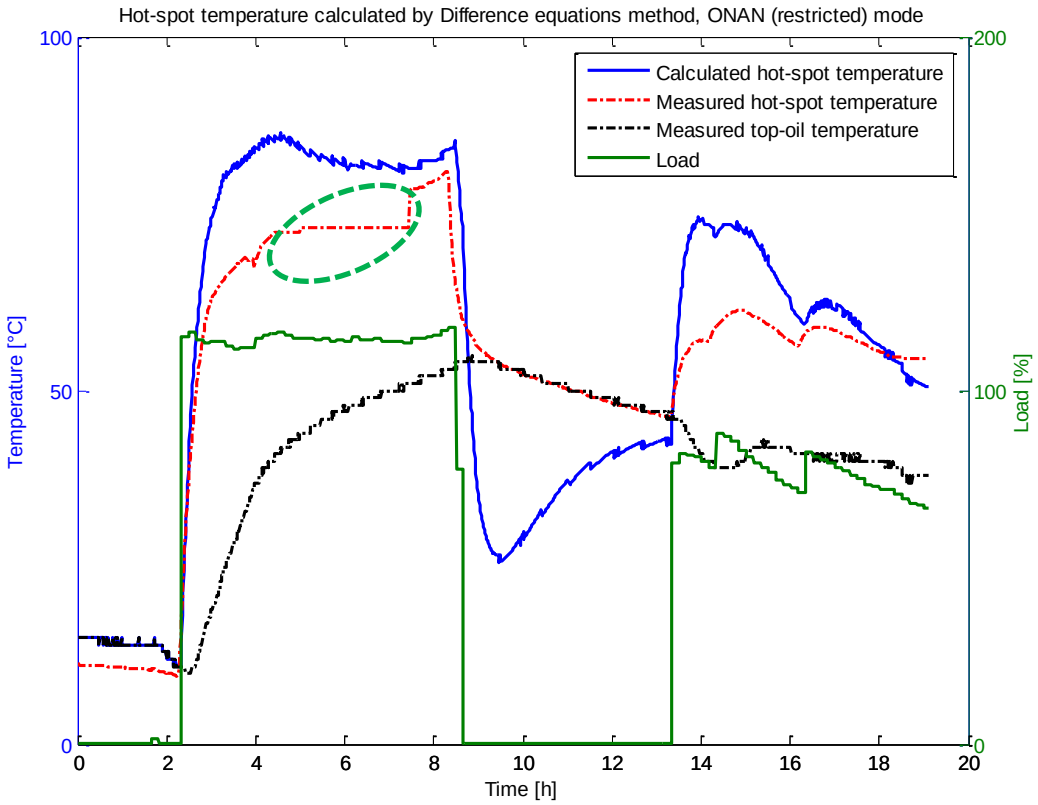

Fig. 38: The calculated hot-spot temperature using the Difference equations method during an overloading period, Tr. 1. The cooling mode is assumed to be ONAN restricted mode. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 37 and 38 show that the calculated hot-spot temperature does not agree well with the measured counterpart considering ONAN restricted cooling mode.

6 Evaluation of Results and Discussion

Fig. 39 depicts a comparison of the measured hot-spot temperature to the calculated hot-spot temperature using the Difference equations method and the Exponential method according to both versions of the IEC standard, i.e. IEC 60076-7 and IEC 354 during a normal loading period.

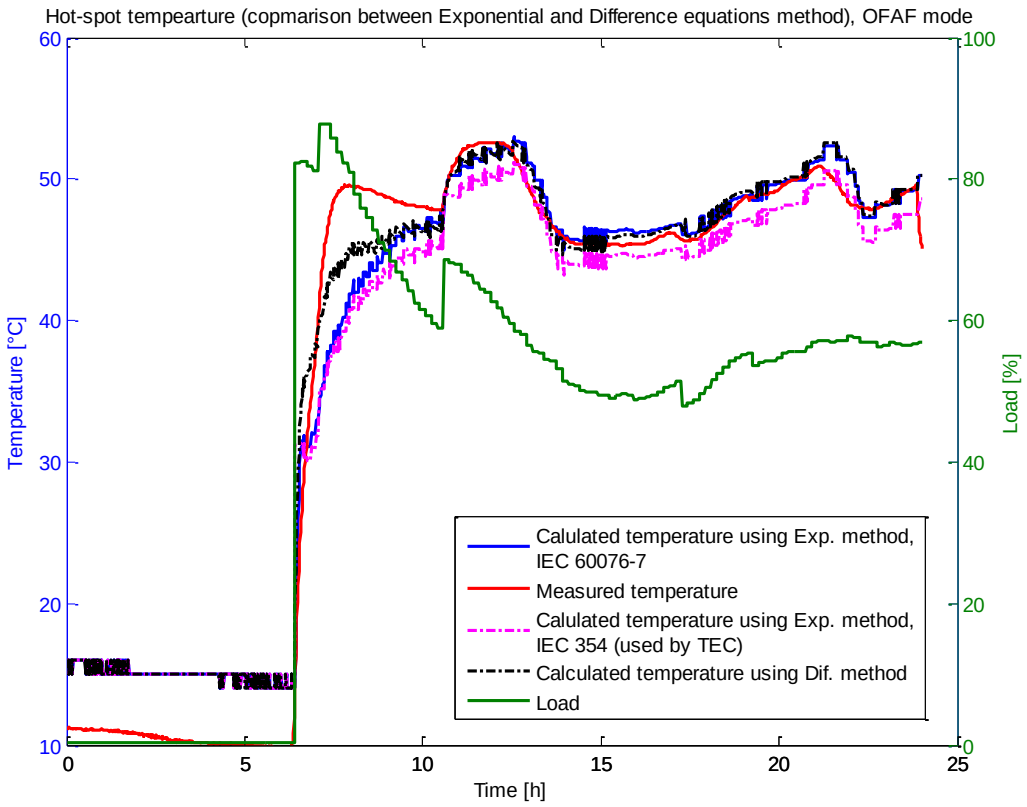

Fig. 39: The calculated hot-spot temperature using Difference equations method and both versions of the Exponential method (IEC 60076-7 and IEC 354) during a normal loading period, Tr. 1.

It is shown in Fig. 39 that, all methods underestimate the hot-spot temperature during a load increase, while the response from the Difference equations method is better than the Exponential method.

Fig. 40 depicts a comparison of the measured hot-spot temperature to the calculated hot-spot temperature using the Difference equations method and the Exponential method according to both versions of the IEC standard, i.e. IEC 60076-7 and IEC 354 during an overloading period.

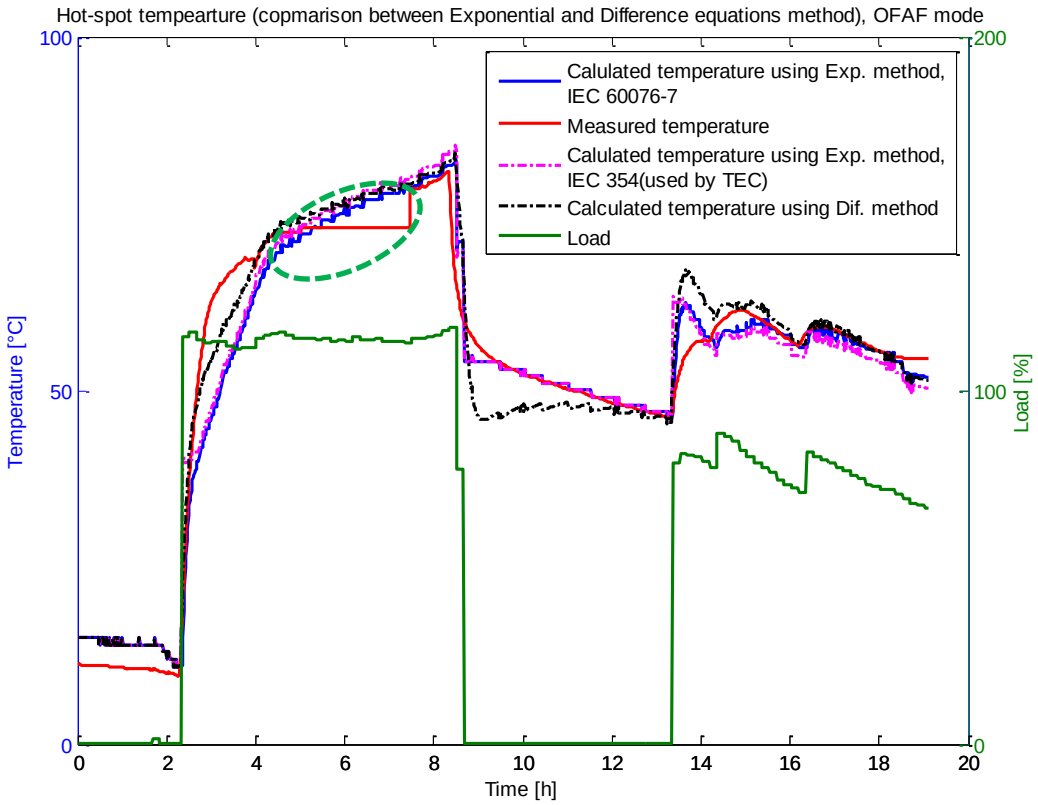

Fig. 40: The calculated hot-spot temperature using the Difference equations method and both versions of the Exponential method (IEC 60076-7 and IEC 354) during an overloading period. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 40 shows that the response from the Difference equations method is better than the other two methods. However, the difference equations method underestimates also the hot-spot temperature under load decrease which is less severe compared to load increase.

The result of hot-spot temperature calculations using Difference equations method and Exponential method (IEC 60076-7) with ONAN cooling mode are depicted in Fig. 41 during a normal loading period and Fig. 42 during an overloading period.

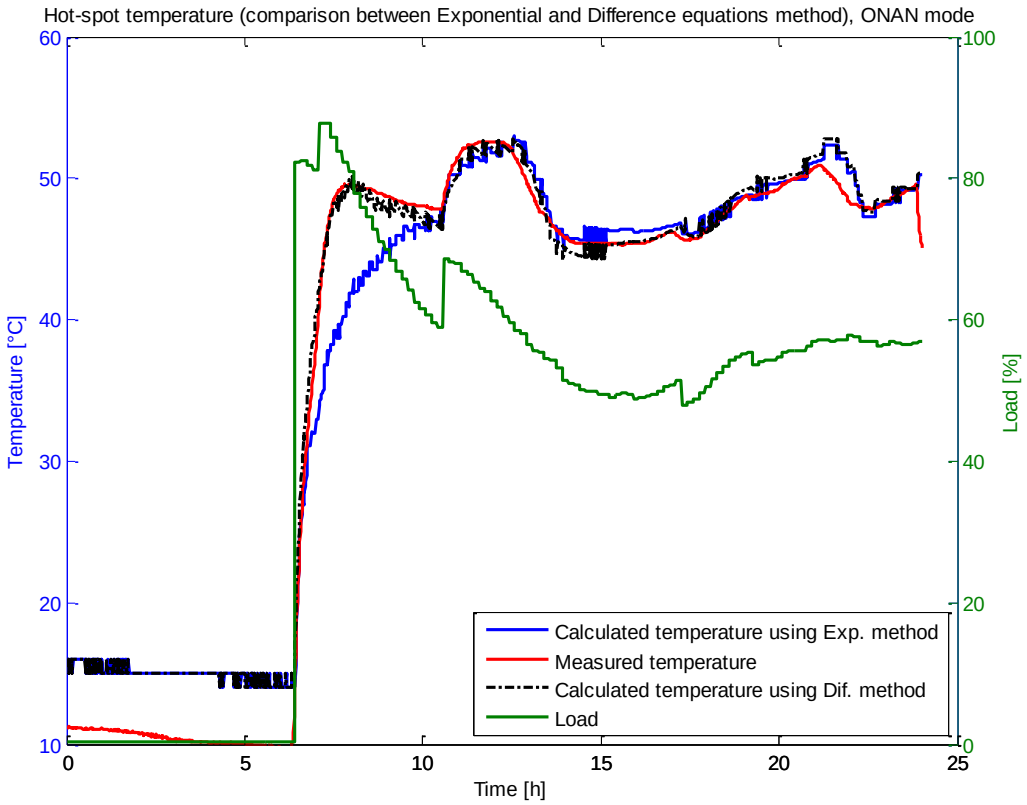

Fig. 41: The calculated hot-spot temperature using Difference equations method and Exponential method (IEC 60076-7) with ONAN cooling mode during a normal loading period, Tr. 1.

Fig. 41 shows that the calculated hot-spot temperature using Differential equations method with ONAN mode is in a good agreement with the measured hot-spot temperature for especially a load increase. The Exponential method underestimates the hot-spot temperature during rapid load increase.

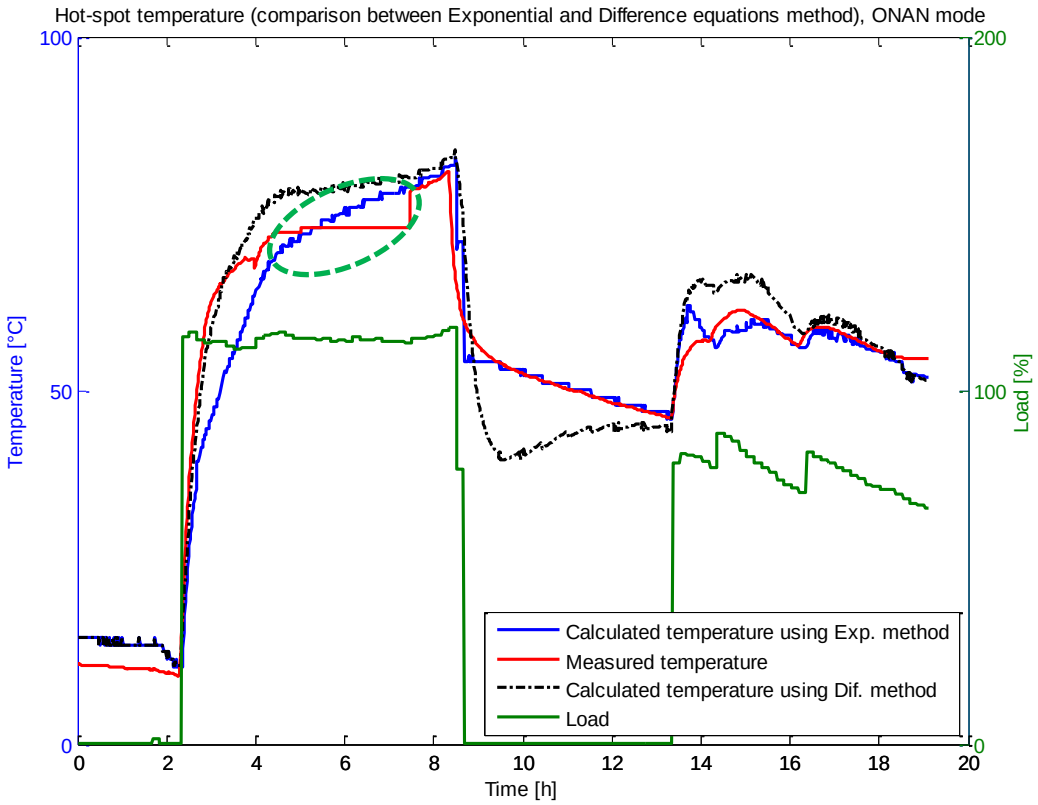

Fig. 42: The calculated hot-spot temperature using the Difference equations method and the Exponential method (IEC 60076-7) with ONAN cooling mode during an overloading period, Tr. 1. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse.

Fig. 42 shows also more accurate result for the Difference equations method during an overloading period, excluding the period occurring an error in the hot-spot temperature measuring system. However, the deviations are higher during load decrease which is less severe compared to the response during load increase.

The error is probably an effect of an overestimating time constant for cooling. For practical applications, however it is not a critical case for transformers, as the system has no risk of overheating during decreasing load as the temperature goes down.

Furthermore, the calculated hot-spot temperature using the Difference equations method with ONAN cooling mode, along with the measured top-oil and hot-spot temperatures and the load during a loading period of seven days, are depicted in Fig. 43.

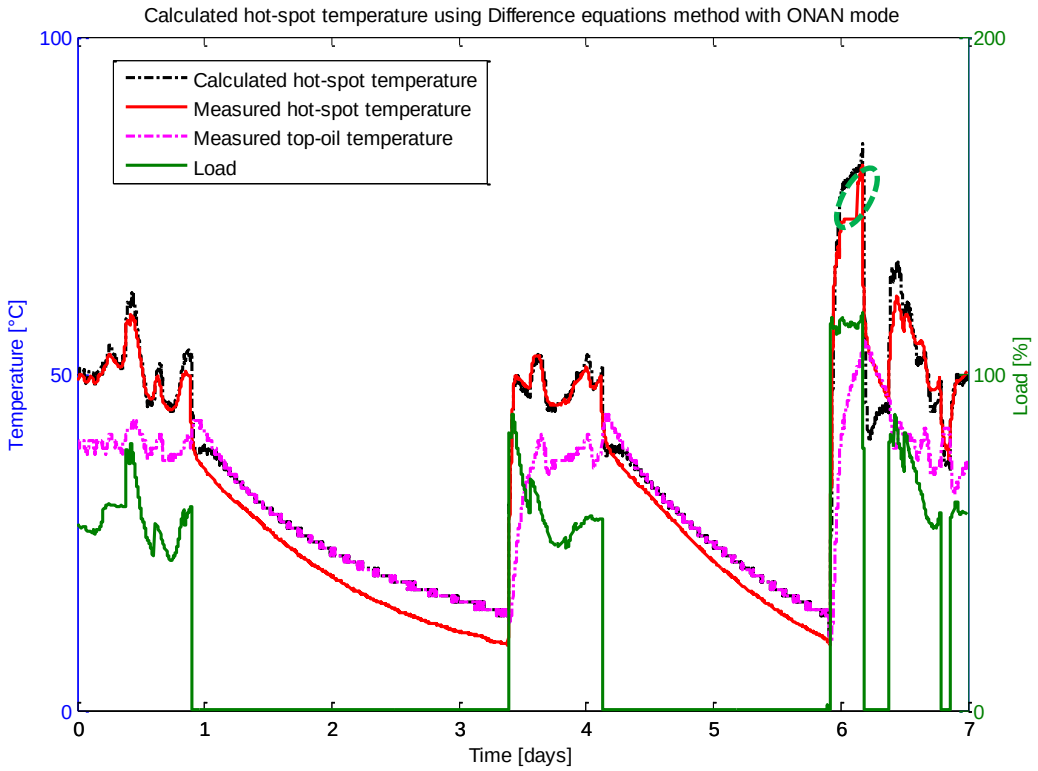

Fig. 43: The calculated hot-spot temperature using Difference equations method during a seven days period of loading, Tr. 1. There is a blind period in the hot-spot temperature measuring system marked by a green ellipse during the overload period (at time=6 days). In addition, during the off-load period the measured top-oil temperature is higher than the measured hot-spot temperature which can be also an error in the measurements.

Fig. 43 shows that the calculated hot-spot temperature using the Difference equations method with ONAN cooling mode follows the measured hot-spot temperature under the load variations for Tr. 1. The calculated hot-spot temperature is higher than the measured hot-spot temperature when the load is about zero, because during these periods the measured top-oil temperature is higher than the measured hot-spot temperature as shown also in the figure.

The results are further evaluated by presenting the deviated hot-spot temperatures between measured values and calculated values in degree Celsius for each method, considering OFAF and ONAN cooling modes. Three ranges of tolerance have been assumed for the deviation, i.e. 3℃, 5℃ and 10℃. How often the deviated values are greater than 3℃, 5℃ and 10℃ is determined in percentage of the time considered. The results are presented in tables (8-11).

Table 8: The underestimation of calculated hot-spot temperature using different methods, in degree Celsius. The hot-spot temperature calculations are performed during a normal loading period.

	Dif. Method, ONAN mode [%]	Exp. Method ONAN mode [%]	Dif. Method OFAF mode [%]	Exp. Method OFAF mode [%]	Exp. IEC 354 (used by TEC) [%]
ΔT[1]$>3°$	0	9.8	7.7	9.8	14.1
$\Delta T > 5°$	0	7.3	1.6	7.3	9.0
$\Delta T > 10°$	0	0.3	0	0.3	2.1

Table 8 shows the rate of occurrence of the underestimated hot-spot temperature calculated during a normal loading period. The deviations are calculated by subtracting the calculated values from the measured values. The result shows that the Difference equations method considering ONAN mode results in a more accurate hot-spot temperature compared to the Exponential method as the largest deviation is 3℃.

Table 9: The overestimation of calculated hot-spot temperature using different methods, in degree Celsius. The hot-spot temperature calculations are performed during a normal loading period.

	Dif. Method, ONAN mode [%]	Exp. Method ONAN mode [%]	Dif. Method OFAF mode [%]	Exp. Method OFAF mode [%]	Exp. IEC 354 (used by TEC) [%]
$-\Delta T > 3°$	27.3	26.9	28.6	27.7	27.7
$-\Delta T > 5°$	2.2	2.1	3.4	2.5	2.8
$-\Delta T > 10°$	0	0	0	0	0.35

Table 9 shows the rate of occurrence of the overestimated hot-spot temperature calculated during a normal loading period and under same conditions as in the table 8. All methods result in almost the same hot-spot temperature overestimation.

[1] ΔT= Measured hotspot temperature − Calculated hotspot temperature.

As it is stated before, there is a blind period in the hot-spot temperature measuring system in about (3.8 h) during the overloading period, exactly between 3.7h and- 7.5h which can be disregarded in the comparisons. Thus, the calculations are performed during load increase excluding the period when the hot-spot temperature measurement had a problem. The results are presented in tables (10-11).

Table 10: The underestimation of calculated hot-spot temperatures using different methods, in degree Celsius. The calculations are performed during increasing load at an overloading period excluding the error period.

	Dif. Method, ONAN mode [%]	Exp. Method ONAN mode [%]	Dif. Method OFAF mode [%]	Exp. Method OFAF mode [%]	Exp. IEC 354 (used by TEC) [%]
$\Delta T > 3°$	9.9	20.0	13.8	19.4	27.7
$\Delta T > 5°$	5.5	17.2	11.1	15.2	13.8
$\Delta T > 10°$	0	12.2	0	12.0	10.5

Table 10 shows the rate of occurrence of the underestimated hot-spot temperature calculated during an overloading period. It can be concluded that, the Difference equations method with ONAN cooling mode gives more accurate result than the other methods during load increase for Tr. 1.

Table 11: The overestimation of calculated hot-spot temperature using different methods, in degree Celsius. The calculations are performed during increasing load at an overloading period excluding the error period.

	Dif. Method, ONAN mode [%]	Exp. Method ONAN mode [%]	Dif. Method OFAF mode [%]	Exp. Method OFAF mode [%]	Exp. IEC 354 (used by TEC) [%]
$-\Delta T > 3°$	35.6	9.7	14.8	9.9	11.7
$-\Delta T > 5°$	20.0	7.0	13.2	7.5	9.9
$-\Delta T > 10°$	3.9	1.8	6.3	1.8	4.3

Table 11 shows the rate of occurrence of the overestimated hot-spot temperature calculated during an overloading period. The Difference equations method still results in a high hot-spot temperature overestimation.

7 Conclusions

A thermal model for hot-spot temperature calculations stipulated by IEC was evaluated using the experimental results obtained by varying the load on Tr. 1. The thermal model can be described by a set of differential equations. Three methods were introduced to solve the differential equations. The Difference equations method was presented in section 3.4.1, the Exponential method according to IEC 60076-7 in section 3.4.2 and the Exponential method according to IEC 354 in section 3.5.1.

The calculated hot-spot temperature was underestimated during the rapid load increase using all three methods under both normal loading and overloading periods. The least deviation between measured and calculated hot-spot temperature was obtained using the Difference equations method during load increase. The Exponential method stipulated by IEC 60076-7 provided a better result than the Exponential method stipulated by IEC 354 during a load increase.

As an undesirable underestimation of the hot-spot temperature often occurred during the rapid load increase, it was suspected that the actual internal cooling state had not been correctly represented in the methods. Thus, the internal cooling variation was included in the model. In order to detect the status of the internal cooling during the operation, the oil flow measurement from the oil pump was used as an indicator for the variation of the cooling mode. This means that the Tr. 1 can sometimes operate as an ONAF transformer although it is an OFAF transformer. However, the model was not applicable for this transformer as the hot-spot temperature is underestimated during load increase. In order to decide the validity of the method for all power transformers, the method should be implemented at least on a second transformer.

A proper model for calculating the hot-spot temperature for Tr. 1 was achieved using the Difference equations method with ONAN cooling mode. The hot-spot temperature was calculated using the model in different load situations. The result of the calculation agrees well with the measured hot-spot temperature compared to the calculations based on nameplate designated cooling class.

The Difference equations method with ONAN mode never underestimated the hot-spot temperature more than 3℃ under normal loading period. For the overloading situation the underestimation was 9.9 % of the time period that is less accurate comparing to the normal loading period. The rate of occurrence of the underestimation was 7.7% for the Difference equations method with OFAF cooling mode during a normal loading period, and 13.8% during an overloading period. However, the Difference equations method with OFAF cooling mode never underestimated the hot-spot temperature more than 10℃ under the normal loading and the overloading situations.

The Difference equations method with ONAN cooling mode provide more accurate result than the other methods in calculating hot-spot temperature in Tr. 1 under load increase although the cooling type of the transformer was OFAF. Thus, it can be concluded that the Tr. 1 was operated with an ONAN cooling mode during rapid load increase and the operational temperature was high because of the reduced cooling efficiency.

There may be several reasons for this phenomenon:

- The oil circulation in the transformer using the oil pump might not be effective and a minor part of the oil may flow through the winding.
- The direction of the oil forced by the pump may counteract the natural oil flow in the windings.
- Reduced oil mass and heat transfer through the windings because of an increased hydraulic resistance.
- The placement of the hot-spot measuring sensor may not be at the right location.
- There can also be errors in the measured top-oil or/and hot-spot temperatures.

The result of the hot-spot temperature calculations using different cooling modes delivers almost vague conclusions. However, the hot-spot temperature can be predicted more accurately if the real status of the cooling in the transformer could represent accurately in the model.

In addition, the top-oil temperature was calculated considering various scenarios. It can be concluded that, the simplicity of the top-oil-to-air model may not be realistic for very cold weather.

8 Outlook

In this chapter, some thoughts for improving the top-oil temperature and hot-spot temperature calculations are suggested as future works.

8.1 Top-oil temperature

- The thermal characteristics of the oil in the transformer is not constant, it is changeable with temperature. The lumped capacitance method used in the model should be modified by introducing nonlinear thermal resistance, which takes changes in the transformer oil thermal parameters with temperature into account [25]. Thus, considering the change of oil viscosity with the temperature during operation of power transformers, dynamic thermal models have been developed in [25], [26], [27], and [28]. The effects of oil viscosity changes on the oil thermal resistance and top-oil time constant have been included in the model. Thus, the oil viscosity changes and the loss variation with temperature are taken into account in the model. A possible future work is to evaluate the validity of the model under dynamic load variations using the available measured top-oil temperature from at least two transformers. Another complementary work could be to take the weather considerations on the site into account.
- The parameters used in the top-oil temperature model presented by Swift, Moliniski and Lehn in [11] can be estimated based on the parameter estimation method suggested by the same authors in [29]. Thus, another possible work in future is to run an optimization program to find the optimum parameters for the model.

8.2 Hot-spot temperature

- The variation in the internal and the external cooling mode can be included in the model for hot-spot temperature calculation, considering the thermal characteristics of the type of the winding. An oil flow measuring device can be installed at the tank oil inlet pipe and the cooler air flow can be calculated, measuring air inlet and outlet temperatures, when the fans are not running, according to [33]. The model has to be implemented on at least two different types of transformers equipped with fibre optic sensors.
- A thermal model for hot-spot temperature calculations has been developed by in [25], [26], [27], and [28]. The model takes into account the change of the thermal resistance and the winding time constant due to the oil viscosity variation with the temperature. A possible work is to implement this model on at least two different types of transformers equipped with fibre optic sensors.

9 References

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Appendices

An example about calculating hot-spot temperature using Exponential method is introduced in appendix A. An example for calculating hot-spot temperature and the loss of insulation life using Difference equations method is introduced in appendix B. in appendix C the Exponential method according to the standard IEC 354, is used to calculate hot-spot temperature instead IEC 60076-7 for the same example introduced in appendix A. The determination of the top-oil and winding time constants are presented in appendix D based on the available data of the transformer. Appendix E shows the various scenarios for top-oil temperature calculations.

Appendix A–Exponential equations method

To show the result of temperature calculations by the Exponential method there is a practical example in [2] which is performed by testing a 250 MVA, ONAF Transformer. The test is done by loading the transformer in a step function; after each decreased load step there is an increased load step and vice versa as shown in table 12. In this appendix, the calculated temperature curves are presented only. Furthermore, the ambient temperature is assumed to have a fixed value during all the time in the test and is 25.6℃.

Table 12: Load steps during a test.

Time period [min]	Load factor
0 – 190	1.0
190 – 365	0.6
365 – 500	1.5
500 – 710	0.3
710 – 735	2.1
735 - 750	0.0

Fig. 44 shows the obtained curves for hot-spot and the top-oil temperatures.

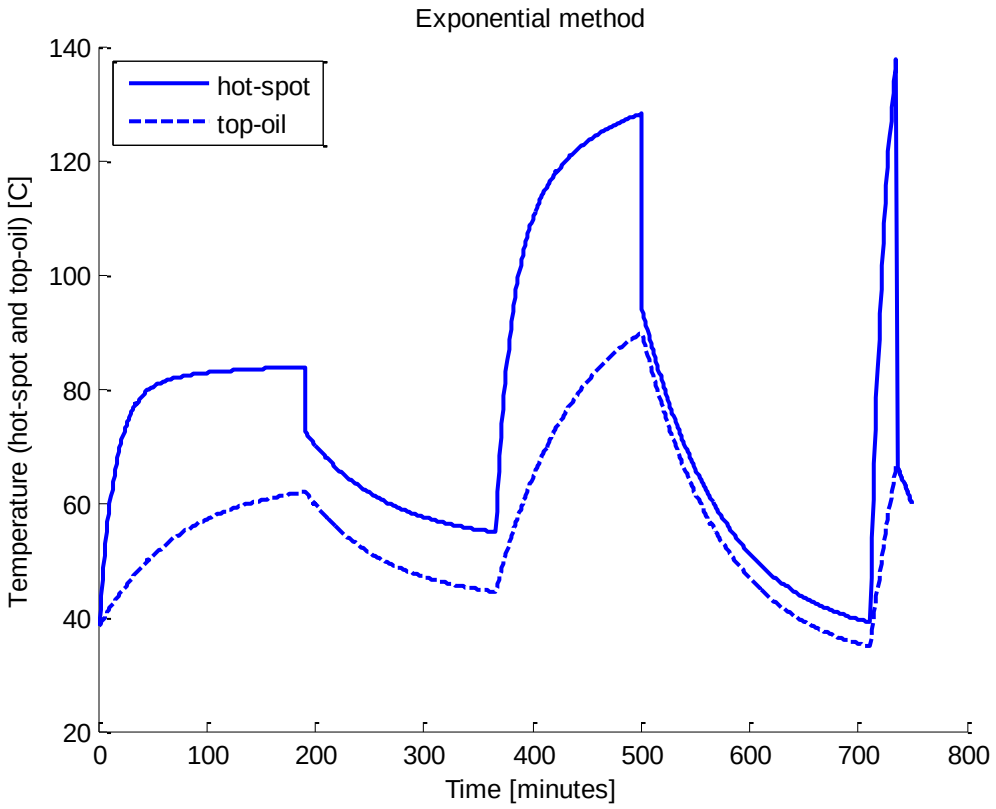

Fig. 44: The values of hot-spot and top-oil temperatures responding to the load variations given in Table 12, using the Exponential method.

Appendix B–Difference equations method

To show the result of temperature calculations by the Difference equations method there is an example in [2]. It is assumed that the objective of the temperature calculation is to on-line monitoring of a transformer therefore a varying ambient temperature and load are the input variables to the model.

Although the system is not strictly in steady state it is assumed that the system is in steady state at the start of the calculations, since it has a little effect on the result.

Fig. 45 shows the input data for the example during two hours, Fig. 46 shows the calculated temperature curve for hot-spot temperature and the calculated loss of insulation life of a transformer is shown in Fig. 48.

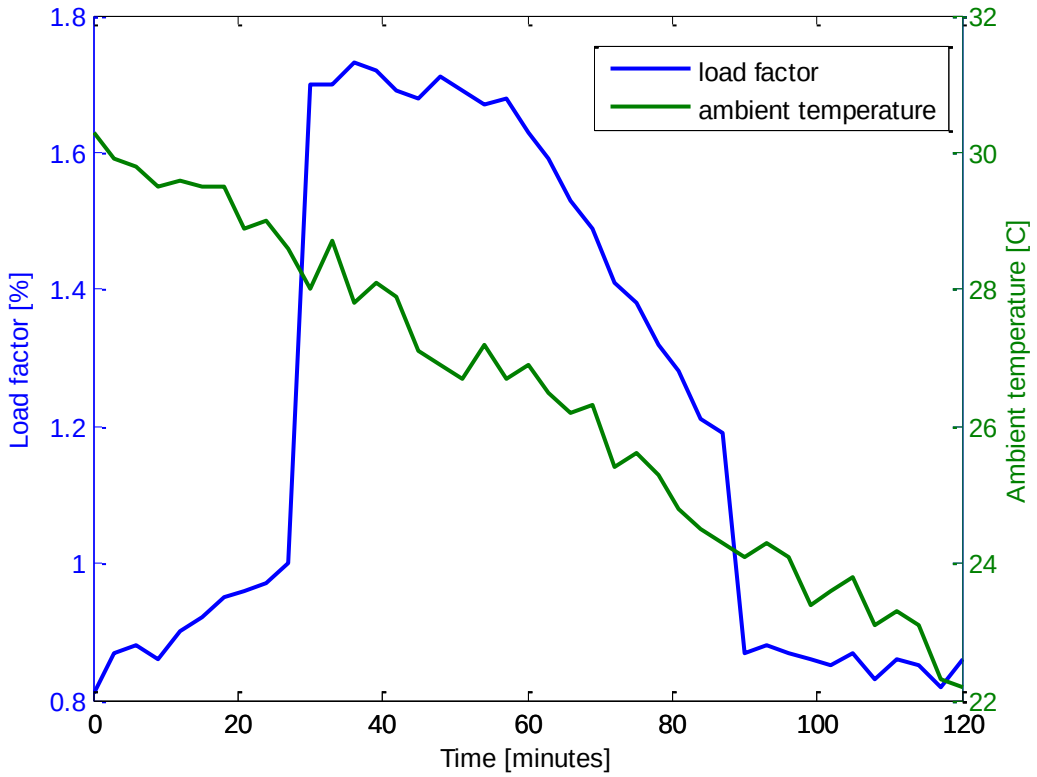

Fig. 45: The varying load and ambient temperature as input variables.

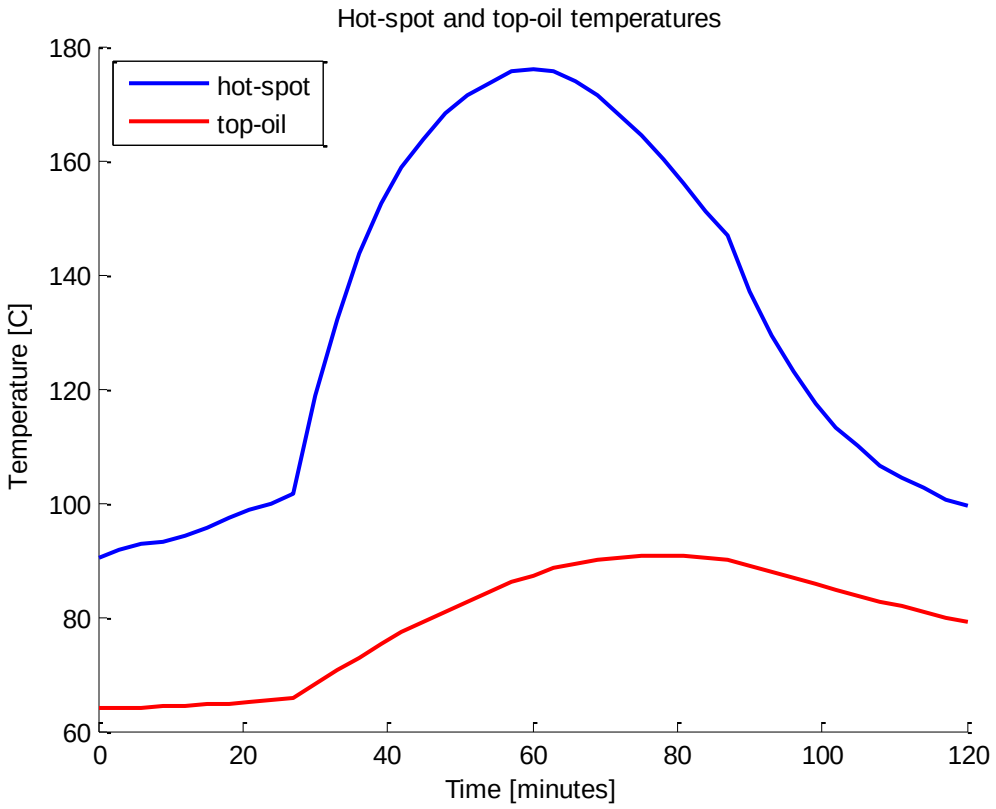

Fig. 46: The calculated top-oil and hot-spot temperatures responding to the load variations shown in Fig. 45, using the Difference equations method.

The Exponential equations method is used for calculating top-oil and hot-spot temperatures instead the Difference equations method for the same example. The results show that the exponential method gives lower temperatures comparing to the difference equations method, as shown in Fig. 47

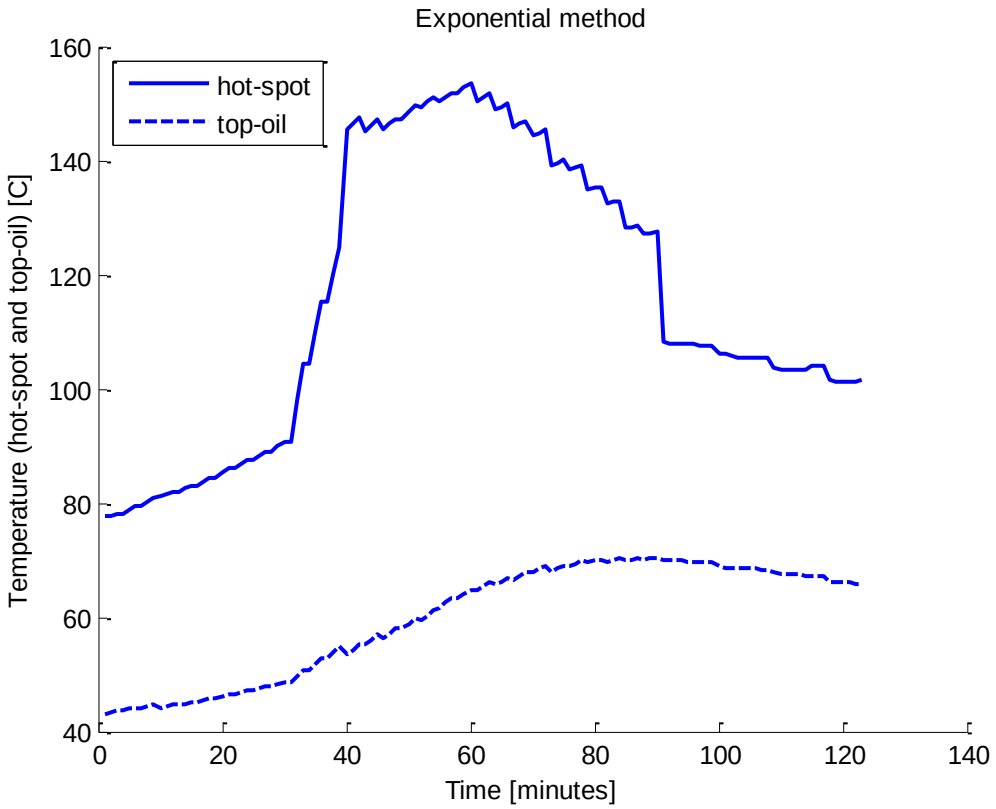

Fig. 47: The calculated top-oil and hot-spot temperatures responding to the load variations shown in Fig. 45, using the Exponential method.

Fig. 48 shows the predicted loss of insulation life considering the calculated hot-spot temperature shown in Fig. 46.

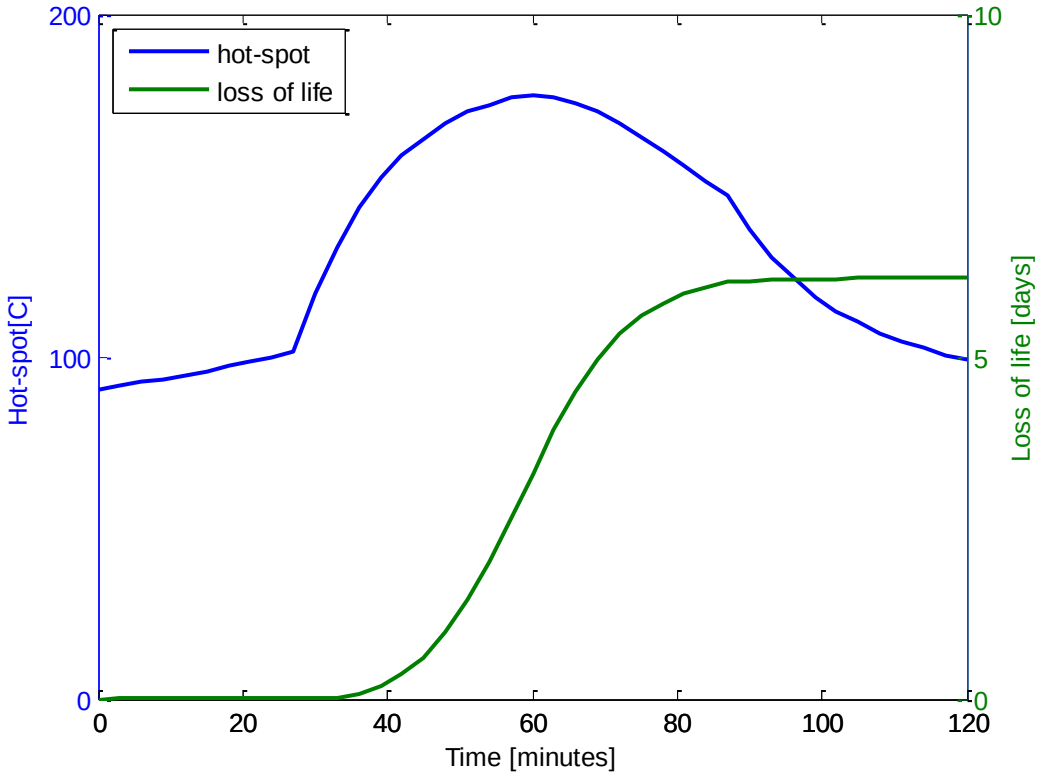

Fig. 48: The calculated loss of insulation life with corresponding hot-spot temperature.

Appendix C—Exponential method IEC 354

The same example in appendix A is repeated using Exponential method according to the IEC 354. For the purpose of comparing both versions of the standard, the calculated temperatures from both methods are presented in the same figure. Fig. 49 shows the calculated top-oil temperatures and Fig. 50 the calculated hot-spot temperatures.

The result shows that the estimated hot-spot temperature by using the new version of the IEC method is higher compared to the old version of IEC method during load increasing.

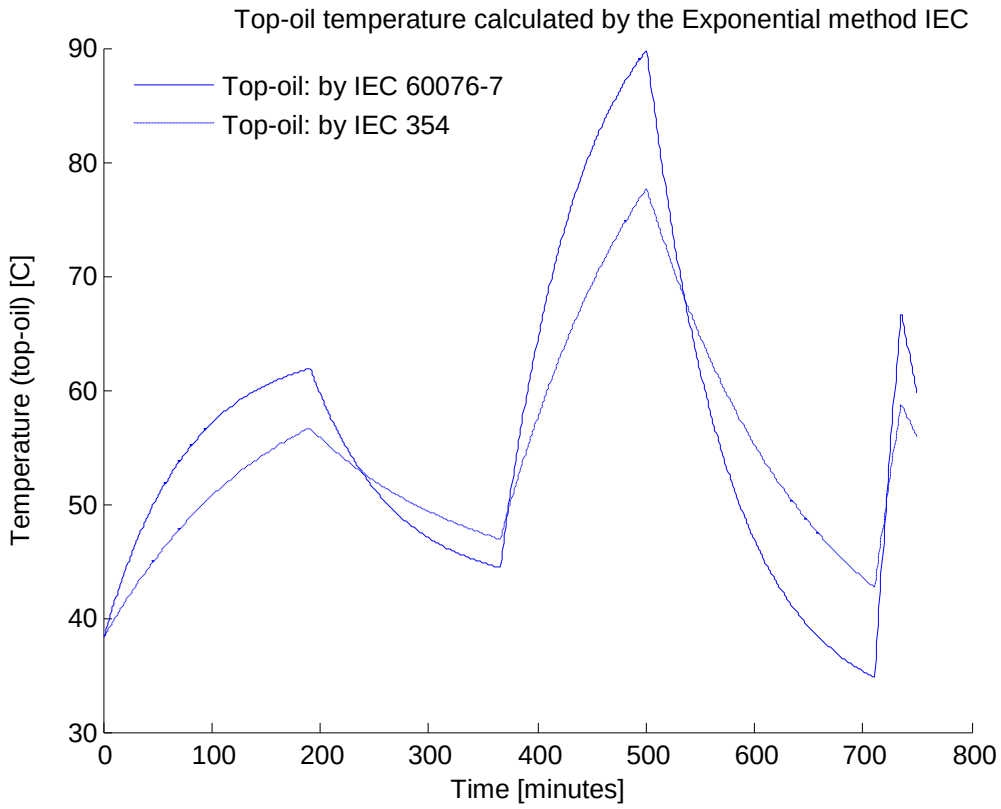

Fig. 49: Comparison between IEC 60076-7 and IEC 354 (used by TEC) for top-oil temperature calculation.

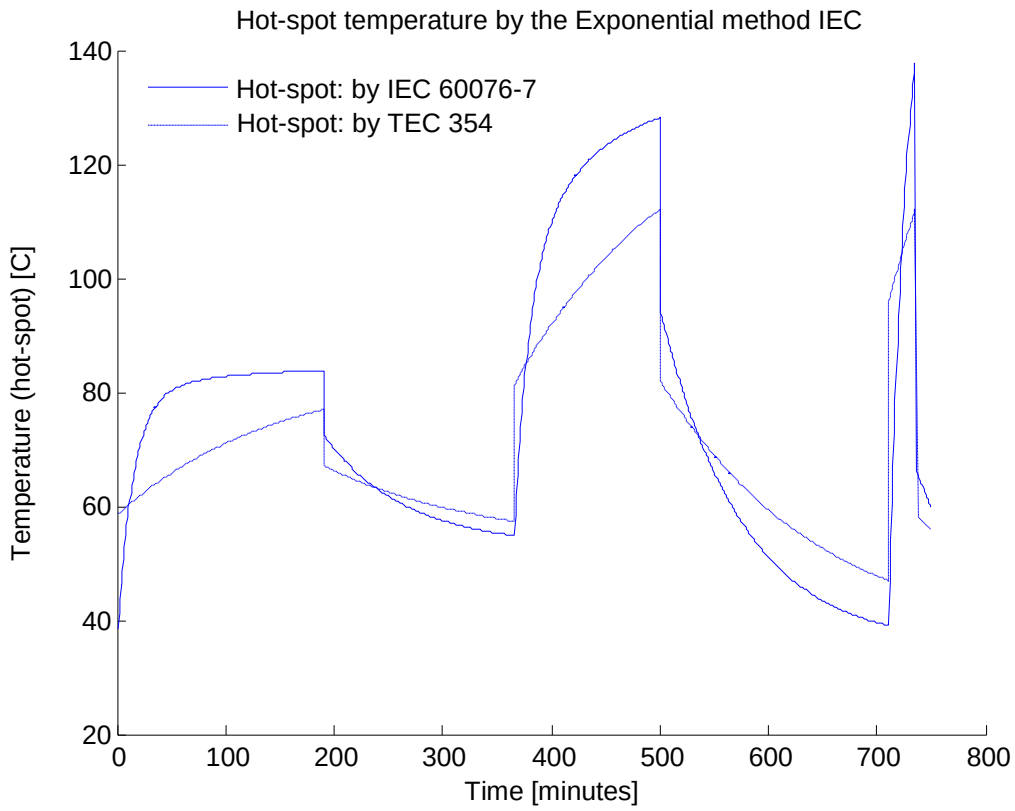

Fig. 50: Comparison between calculated hot-spot temperatures using IEC 60076-7 and IEC 354 (used by TEC).

Appendix D– Determination of oil and winding time constants

According to the IEC standard [2], the winding and oil time constants can be calculated if the transformer data from the test is available. The necessary data and the formulas for the calculation are presented below.

The winding time constant τ_w in [min] is calculated according to the following formula:

$$\tau_w = \frac{m_w \times c \times g}{60 \times P_w},$$

The oil time constant τ_o in [min] is calculated according to the following formula:

$$\tau_o = \frac{C \times \Delta\theta_{om} \times 60}{P}.$$

Where

m_w is the mass of the winding in [kg],

c is the specific heat in the conductor (390 for Cu and 890 for Al) in [W.min/kg.K],

g is the winding-to-oil gradient at the load considered in [K],

P_w is the winding loss in [W] at the load considered.

C is the transformer thermal capacity in [W.min/K].

$C = 0.132 \times m_A + 0.0882 \times m_T + 0.400 \times m_O$ (for natural oil-cooling modes, either ONAN or ONAF)

$C = 0.132 \times (m_A + m_T) + 0.580 \times m_O$ (for the forced-oil cooling modes, either OF or OD)

m_A is the mass of core and coil assembly in [kg],

m_T is the mass of the tank and fittings, those portions that are in contact with heated oil, in [kg],

m_o is the mass of oil in [kg].

$\Delta\theta_{om}$ is the average oil temperature rise above ambient temperature in [K] at the load considered.

P is the supplied losses (total losses) in [W] at the load considered.

Appendix E—The result of the calculation for top-oil temperature

In this appendix the more results for the calculated top-oil temperature using the scenarios given in section 4.1 for both Tr. 1 and Tr. 2 are presented.

Transformer one

Fig. 51 shows the comparison between the measured top-oil temperature of Tr. 1 and the calculated top-oil temperature considered the third scenario. The calculation is performed using the Difference equations method. The top-oil temperature is underestimated with a high error.

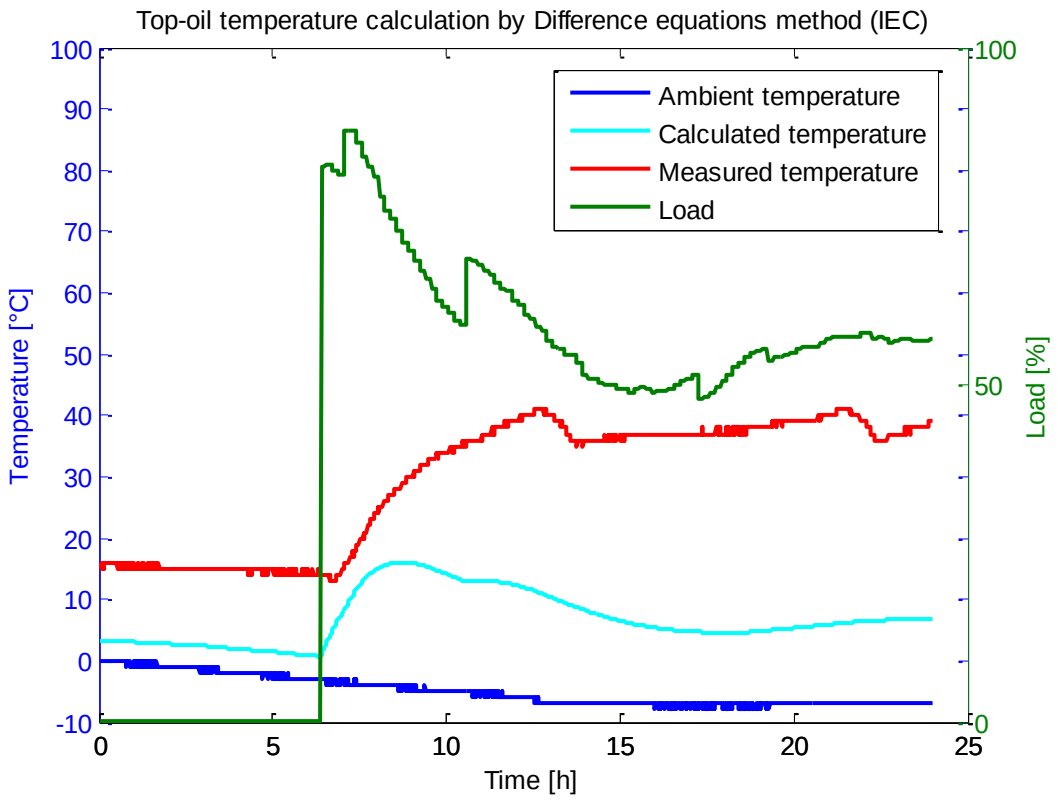

Fig. 51: The top-oil temperature response calculated by the Difference equations method during a normal loading period (the actual ambient temperature is a variable input to the model), Tr. 1.

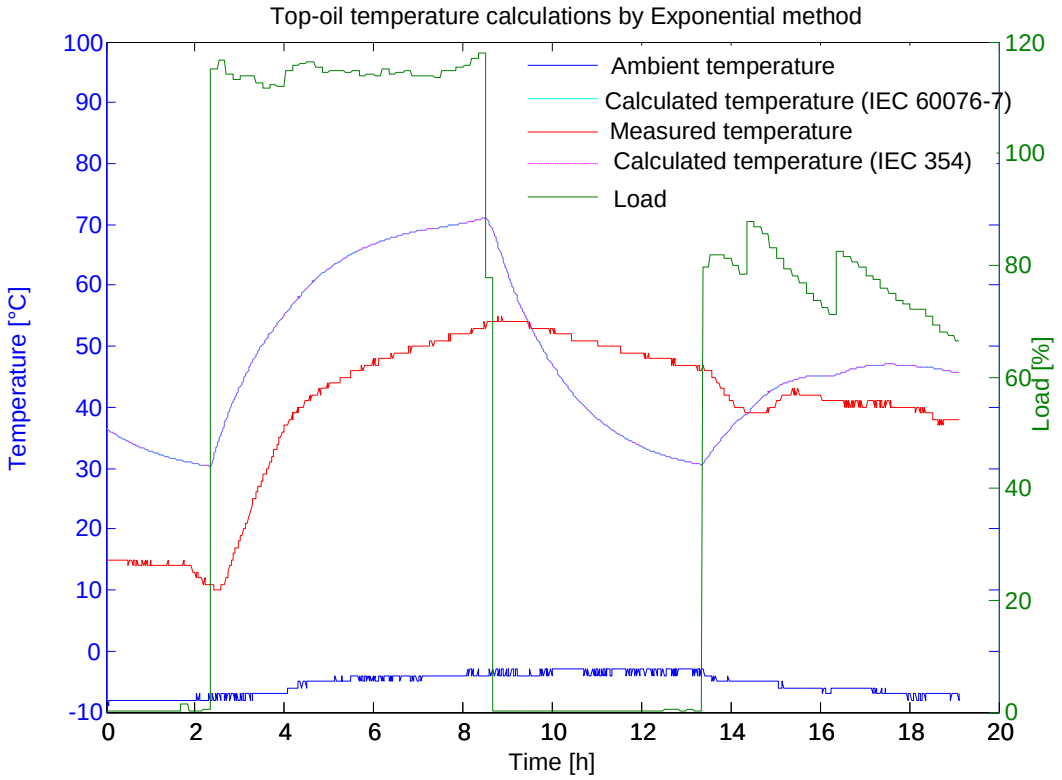

Fig. 52: The calculated top-oil temperature using the Exponential method during an overloading period (a constant ambient temperature of 25℃ is used in the calculation), Tr. 1.

Fig. 52 shows the calculated top-oil temperature response to the load step changes during an overloading period considering the second scenario. The red curve represents the measured top-oil temperature from the oil temperature indicator. As was also the case for normal loading period in the previous section the calculated top-oil temperature has a higher value for increasing step of loads but lower value for decreasing load steps. At the peak load of about 118% of the rated load, the calculated top-oil temperature is 71℃ for which the measured top-oil temperature is 54℃, means a deviation of 17℃. It is also shown that the calculated top-oil is decreasing faster than the measured top-oil, regarding the oil time constant.

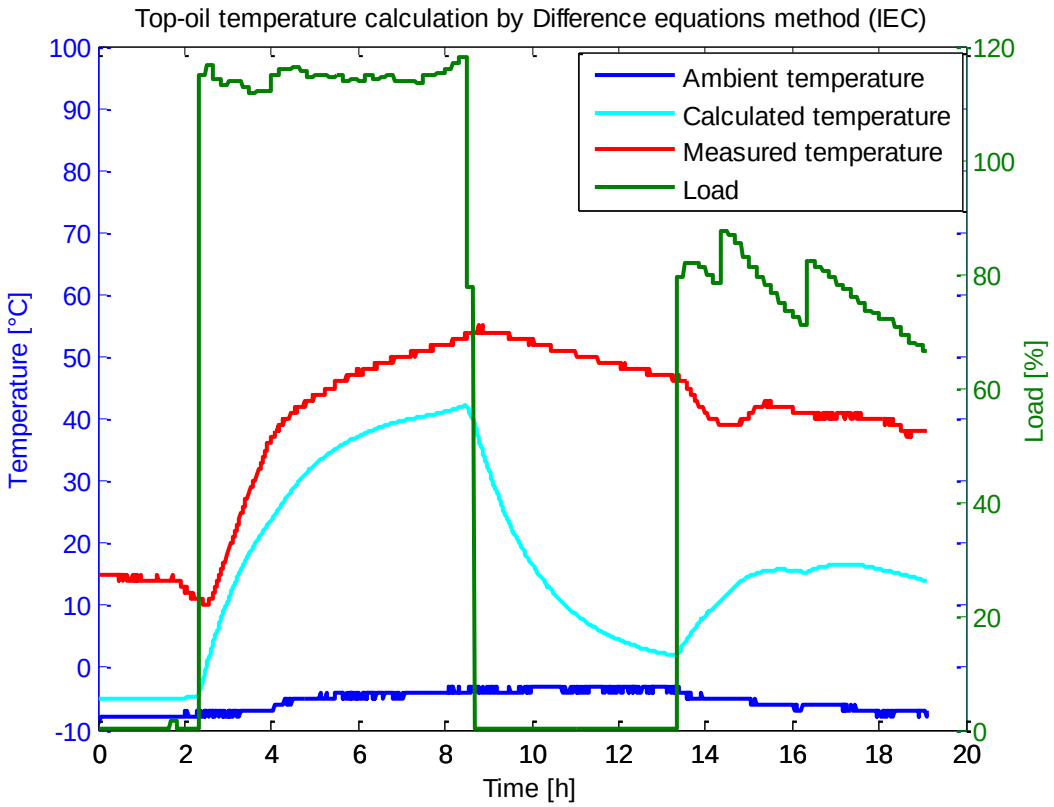

Fig. 53: The top-oil temperature response calculated by using the Difference equations method during overloading period (the actual ambient temperature is a variable input to the model), Tr. 1.

Fig. 53 shows the result of the top-oil temperature calculation considered the third scenario during an overloading period. The red curve is the measured top-oil temperature from the oil temperature indicator. The top-oil increases with increasing load step to 120% of the rated from almost zero load and then decrease slower with decreased load step to about zero again. However, the calculated top-oil temperature has a bad response for the load change. The calculated values are very low and decrease very fast during decreased load step to zero.

Result for transformer two

The top-oil temperature is calculated considering the second scenario in section 4.1. The result of the calculation is depicted in Fig. 54.

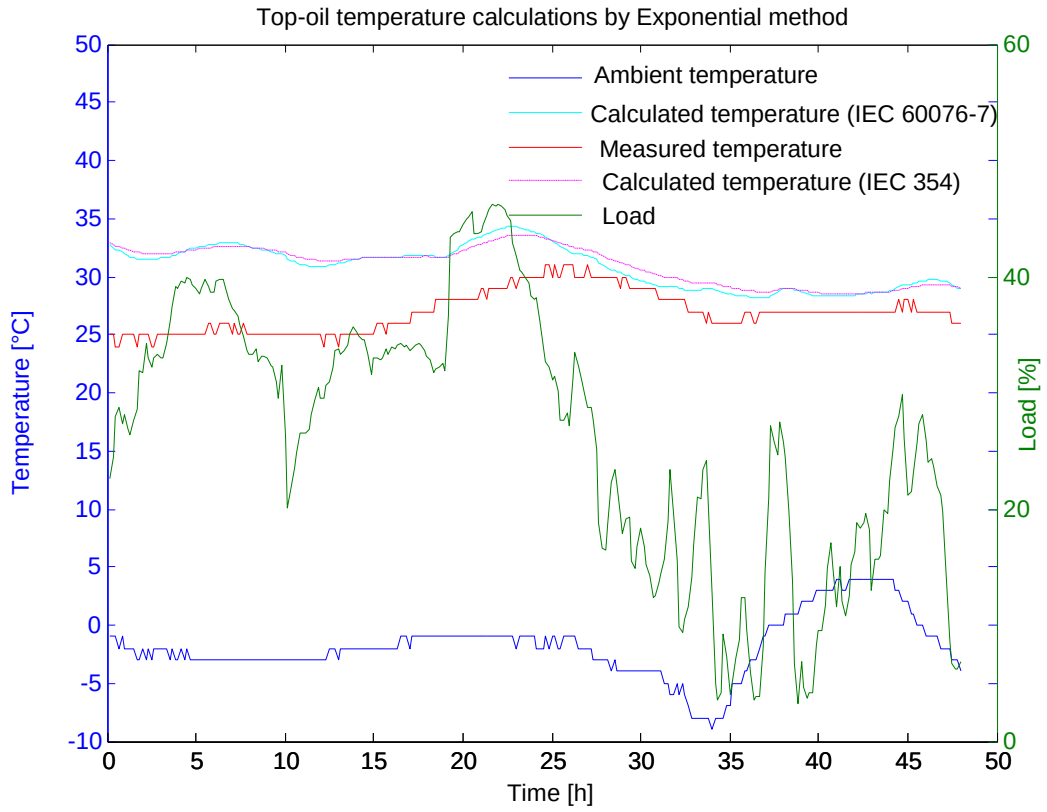

Fig. 54: the top-oil temperature response calculated by the Exponential method during a normal loading (a constant ambient temperature of 25℃ is used in the calculation), Tr. 2.

Fig. 54 shows the top-oil temperature calculations and the red curve shows the measured top-oil temperature from the oil temperature indicator. There are deviations between the calculated and measured temperatures during load increasing variations, around 35-40% of the rated load, but fewer deviations during load decreasing variations, around 10-15% of the rated load.

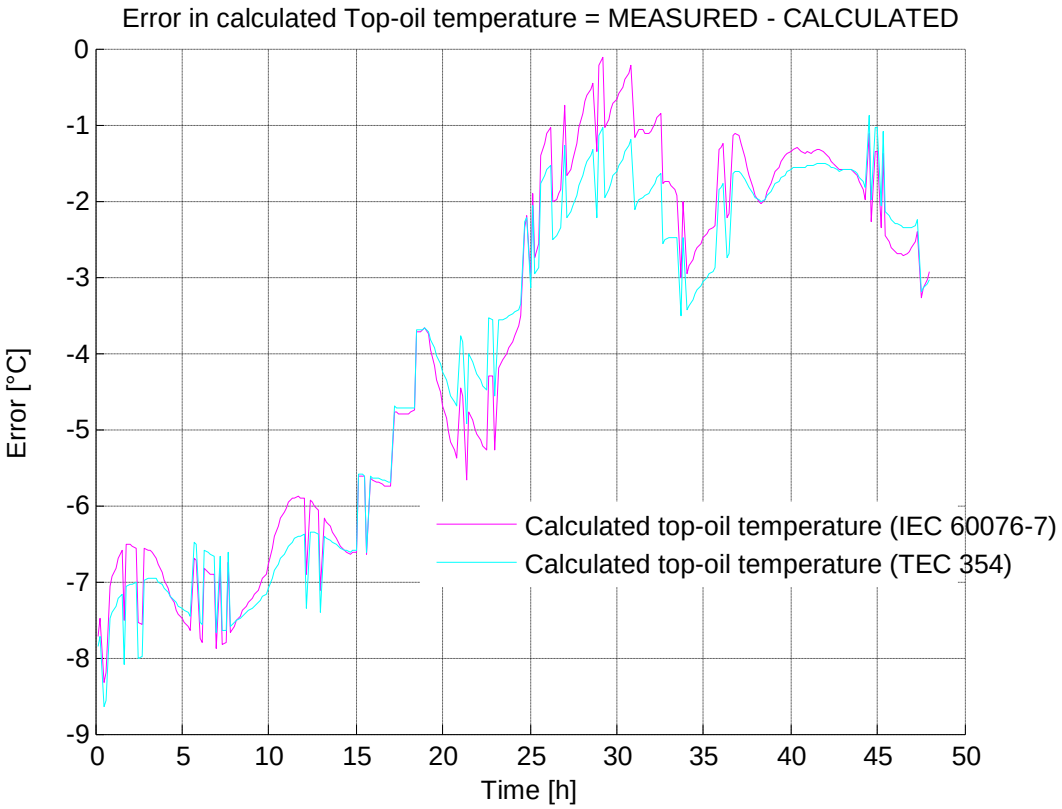

Fig. 55: The estimated error in the calculated top-oil temperature using the Exponential method according to both versions of the IEC standard in Fig. 22.

Fig. 55 shows the deviations between the calculated and the measured top-oil temperatures. It is shown that the top-oil temperature is overestimated in the calculations.