

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO



# **Digital Asset Management - Overload Capacity of Power Transformers**

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# Resumo

Os Transformadores de Potência são componentes da rede eléctrica de extrema importância no que diz respeito à qualidade de serviço de fornecimento de energia. A distribuição dos ciclos de carga estão a ficar cada vez mais imprevisíveis, o que afecta o funcionamento da rede eléctrica caso não seja gerido de forma inteligente. O crescimento tecnológico que se dá nos dias de hoje torna possível a sensorização de activos críticos da rede de forma a extrair dados vitais para monitorização do desempenho destes. A interligação de toda a rede eléctrica por meio de plataformas de gestão inteligente torna todo o processo mais autónomo e eficiente. A sobrecarga de transformadores pode ser uma situação necessária para garantir o contínuo fornecimento de energia, a qual necessita de ser monitorizada de forma a garantir a operação segura do transformador, uma vez que este é um dos activos mais caros de toda a rede. A determinação da capacidade de sobrecarga destes transformadores constitui um aspecto que se traduz numa maior transparência e controlo sob estes activos.

Partindo do modelo térmico proposto pela norma IEC 60076-7 foi desenvolvido um algoritmo que avalia a capacidade de sobrecarga de um transformador de potência. Foi aplicado a um caso real de onde se obtiveram resultados válidos mas de igual forma se verificou que a qualidade dos resultados retornados é afectada pelos dados de entrada como os parâmetros do modelo térmico que parametrizam o transformador.

É demonstrado o papel importante que sobrecarregar Transformadores de Potência pode ter em diversas situações, isto sempre com o objectivo de manter a qualidade de serviço.

Concluiu-se que apesar de se ter cumprido o objectivo de desenvolver um algoritmo de determinação da capacidade de sobrecarga de Transformadores de Potência, devido a limitações nos dados relacionados com a parametrização térmica dos transformadores, a validação e avaliação deste algoritmo não foram executadas em todo o seu potencial. Apesar disto, o conhecimento acumulado levou à formação de um ponto de partida e recomendações para futuros trabalhos relacionados com este projecto.



# Abstract

Power Transformers are components of the electrical network of extreme importance with regard to the quality of service of power supply. The distribution of loading cycles is becoming increasingly unpredictable, which affects the operation of the electrical grid if isn't managed intelligently. The technological growth that takes place in our days makes it possible to digitalize critical network assets in order to extract vital data to monitor their performance. The interconnection of the whole electricity network through intelligent management platforms makes the entire process more autonomous and efficient. Transformer overload can be a necessary situation to ensure continuous power supply, which needs to be monitored in order to ensure the safe operation of the transformer, important factor as it is one of the most expensive assets in the entire network. The determination of the overload capacity of these transformers is an aspect that translates into greater transparency and control of these assets. Starting from the thermal model proposed by the standard IEC 60076-7 an algorithm was developed that evaluates the overload capacity of a power transformer. It was applied to a real case from which we obtained valid results but also was verified that the quality of the returned results is affected by the input data such as the parameters of the thermal model that parameterize the transformer.

It is demonstrated the important role that overloading Power Transformers can have in various situations, aiming always at maintaining the quality of service. It was concluded that, although the objective of developing an algorithm to determine the overload capacity of Power Transformers was accomplished, due to limitations in the available data regarding thermal parameterization of transformers, the validation and evaluation of this algorithm were not performed at all its potential. Despite this, the accumulated knowledge has led to the so needed creation of a starting point and recommendations for future work related to this project.



# Agradecimentos

Quero agradecer à minha família que possibilitou toda esta jornada ao ponto em que estou hoje, pela educação, valores e possibilidades que me deram.

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Helder Martins





*“If you can’t explain it simply, you don’t know it well enough”*

Albert Einstein



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## Symbols and Abbreviations

$C$	Thermal capacity (Ws/K)
$c$	Specific heat (Ws/kg.K)
DTM	Dynamic Thermal Model
DTR	Dynamic Thermal Rating
$g_r$	Average-winding-to-average-oil (in tank) temperature gradient at rated current (K)
$H$	Hot-spot factor
$K_{11}$	Thermal model constant
$K_{21}$	Thermal model constant
$K_{22}$	Thermal model constant
$K$	Load factor (load current/rated current)
IEC	International Electrotechnical Commission
$L$	Total ageing over the time period considered (h)
$m_A$	Mass of core and coil assembly (kg)
$m_T$	Mass of the tank and fittings (kg)
$m_O$	Mass of oil (kg)
$m_W$	Mass of winding (kg)
$n$	Number of each interval
$N$	Total number of intervals during the time period considered
OD	Either ODAN, ODAF or ODWF cooling
OF	Either OFAN, OFAF or OFWF cooling
ON	Either ONAN or ONAF cooling
$P$	Supplied losses (W)
$R$	Ratio of load losses at rated current to no-load losses at rated current
$t$	Time variable (min)
$V$	Relative ageing rate
$V_n$	Relative ageing rate during interval $n$
WTI	Winding temperature indicator
$x$	Exponential power of total loss versus top-oil (in tank) temperature rise (oil exponent)
$y$	Exponential power of current versus winding temperature rise (winding exponent)
$\theta_a$	Ambient temperature (°C)
$\theta_h$	Winding hot-spot temperature (°C)
$\theta_o$	Top-oil temperature (in tank) at the load considered (°C)
$\tau_o$	Oil time constant (min)
$\tau_w$	Winding time constant (min)
$\Delta\theta_h$	Hot-spot-to-top-oil (in tank) gradient at the load considered (K)
$\Delta\theta_{hi}$	Hot-spot-to-top-oil (in tank) gradient at start (K)
$\Delta\theta_{hr}$	Hot-spot-to-top-oil (in tank) gradient at rated current (K)
$\Delta\theta_o$	Top-oil (in tank) temperature rise at the load considered (K)
$\Delta\theta_{oi}$	Top-oil (in tank) temperature rise at start (K)
$\Delta\theta_{or}$	Top-oil (in tank) temperature rise in steady state at rated losses (no-load losses + load losses) (K)

# Chapter 1

## Introduction

### 1.1 Company Presentation

Efacec Power Solutions is the largest Portuguese corporation working in fields like energy, engineering and mobility. With more than 70 years of history, Efacec has a strong exporter profile, operating in over 65 countries.

With innovation and technological development as the main objectives, in the energy market, Efacec, due to his flexibility, can deliver solutions from Core and Shell Power Transformers to Distribution Transformers, as well as the versatile Mobile Substations.

Recognised as a prestigious brand and one of the largest industries in the country, Efacec foresees solutions for a sustainable world in the new energy Era.

### 1.2 Contextualization

With today's exponential technological advances, in the world of energy networks it is now possible to sensorize critical assets with the objective of extracting fundamental data from their operation. This, through computational algorithms, can be transformed into information both for tools to support decision-making in asset management and for tools to predict the maintenance of assets.

The rapid development of power grids and the increase in energy demand make the distribution of load cycles on the energy supply network increasingly unpredictable. Due to economic reasons, the use of the equipment of the network to the maximum of its capability's is getting increasingly important, being limited by the risk of damaging the equipment, in this case power transformers, due to loads above the maximum limits, leading to accelerated ageing of the insulation as well as other components.

### 1.3 Motivation

Given all the possibilities that the creation of intelligent energy networks can achieve, from a vast knowledge acquired by experience as a manufacturer and service provider of assets to power grids, Efacec believes that the provision of a service of diagnosis and maintenance more predictive and intelligent is a differentiating factor in the market in which it is inserted.

The innovation in the direction of a greater digitalization of the physical assets and its integration with other systems directly linked to the value chain leads to a service of diagnosis and maintenance of power transformers, more automated and based on computational algorithms. This automation leads to a much more efficient and intelligent energy network, with greater flexibility in operating conditions, making it possible to make better decisions taking into account much more data and information than ever before.

### 1.4 Objectives

From this dissertation, based on the Efacec accumulated knowledge, it is intended to build an Overload Capacity Algorithm.

It is intended to implement this model and its application in a real case for later analysis and evaluation.

All the knowledge generated aims at contributing to the great effort that is and will continue to be made to the digital transformation of the entire network, making it a smarter one.

### 1.5 Methodology and Planing

The tasks to be completed during the duration of the dissertation can be separated into three main groups:

- Information Collection;
- Solution Development;
- Performance Evaluation;

The method that will be used for the development of this project in the Information Collection phase, in a first instance, will go through the state of the art review regarding the subject, the collection of all that is currently implemented by the company as well as the whole knowledge that comes from the experience gained from this that can be useful in the development of the new model.

In the Development of the Solution phase, a model for calculating the Transformer Overload Capacities is made. After this, the model is implemented with computer support, each of these phases being supported by a test step and finally applied to a real case.

Finally, from the application to the real case the data is analyzed in order to extrapolate conclusions about the viability of the model through statistical analysis as well as the possible comparison of calculated values with real values.

The following plan is done with a weekly time division, the deadline for this project being planned 2 weeks before the official deadline in order to create a margin for possible setbacks, Table 1.1.

- State of the art review (3 weeks)
- Efacec methodology survey (2 weeks)
- Efacec Knowledge Gathering (1 week)
- Construction of the overload capacity model (4 weeks)
- Model implementation / programming (1 week)
- Application of the implementation to a real case (3 weeks)
- Results analysis (2 weeks)
- Verification and validation (1 week)
- Writing of dissertation (Total duration)

## 1.6 Structure

This chapter is intended to provide an introduction to the project developed as well as the objectives to be achieved.

In the second chapter are defined the theoretical concepts in which the algorithm will be based on. In the third chapter a solution is proposed. Data from a real transformer is presented and a methodology is described to verify and evaluate the algorithm.

The fourth chapter presents the results from the tests made.

In the fifth chapter the results and the algorithm are discussed and well as other aspects are pointed out concerning the role that overloading transformers has and may have.

Chapter six describes future work in the context of the project developed.

The seventh chapter overall conclusions are taken regarding the results obtained as well as all the limitation encountered in the development of this project.

Phase	Week																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
State of the art review																				
Efacec methodology survey																				
Efacec Knowledge Gathering																				
Construction of the overload capacity model																				
Model implementation / programming																				
Application of the implementation to a real case																				
Results analysis																				
Verification and validation																				
Writing of dissertation																				

Table 1.1: Project plan

## Chapter 2

# Literature Review

### 2.1 Transformer Fundamentals

Transformers are static devices that transfer electrical energy from one circuit to another by the phenomenon of electromagnetic induction. They can link circuits that have the same voltage, for maintaining only a certain degree of electrical insulation as well as different voltages, which is one of the enabling factors for the universal use of the alternating current (AC) system for the transmission and distribution of electrical energy. Hence, transformers ensure that various components of the power system, viz; generators, transmission lines, distribution networks and loads, can all be operated at their most suitable voltage levels. As transmission voltages are increased to higher levels in some parts of a power system, transformers again play a key role in interconnecting the different parts of the system at different voltage levels. Transformers are therefore vital links between the generating stations and the points of utilization in any system. The transformer is an electromagnetic conversion device in which the electrical energy received by its primary winding is first converted into magnetic energy, which is re-converted into electrical energy in other circuits (secondary winding, tertiary winding, etc.). Thus, the primary and secondary windings are not connected electrically, but coupled magnetically. A transformer is termed either a step-up or a step-down transformer depending upon whether the secondary voltage is higher or lower than the primary voltage. Transformers can be used to either step-up or step-down voltage depending upon the need and application; hence, their windings are referred as high-voltage/low-voltage or high-tension/low-tension windings instead of primary/secondary windings. [10].

### 2.2 Cooling methods

The identification of transformers by the cooling method is made by a 4 letter code, [11]. The first letter represents the internal cooling medium:

- O: mineral oil or synthetic liquid with fire point  $\leq 300$  °C;
- K: insulating liquid with fire point  $> 300$  °C;

- L: insulating liquid with no measurable fire point.

The second letter represents the circulation mechanism for internal cooling medium:

- N: natural thermosiphon flow through cooling equipment and in windings;
- F: forced circulation through cooling equipment, thermosiphon flow in windings;
- D: forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings.

The third letter represents the external cooling medium:

- (A) air;
- (W) water.

The fourth letter represents the circulation mechanism for external cooling medium:

- (N) natural convection;
- (F) forced circulation (fans, pumps).

The following 4 letter codes represent examples of the cooling method identification:

- ONAN - Natural oil and natural air;
- ONAF - Natural oil and Forced air;
- ODAF - Directed oil and Forced air.

### 2.3 Relative Ageing Rate

The insulation deterioration is a time function that depends of the values of temperature, moisture content, oxygen content and acid content. The model presented in IEC 60067-7, [3], is based only on the insulation temperature as the controlling parameter.

The temperature of the transformer does not show an uniform distribution, so the components that reach higher temperatures normally undergo the greatest deterioration. Therefore, the rate of ageing is referred to the winding hot-spot temperature.

The relative ageing rate is  $V$  is given by the Equation 2.1 for transformers equipped with non-thermally upgraded and by Equation 2.2 for thermally upgraded paper, [12].

$$V = 2^{(\theta_h - 98)/6} \quad (2.1)$$

$$V = e^{\left(\frac{15\,000}{110+273} - \frac{15\,000}{\theta_h+273}\right)} \quad (2.2)$$

Where:

$\theta_h$  is the hot-spot temperature in °C.



## 2.4 Loss-of-life calculation

In order to quantify the impact of applying a certain load relative to the life time of the transformer, by combining the relative ageing rate and the duration of the load, the loss of life  $L$ , in time units, result of the load applied over a certain period of time is equal to:

$$L = \int_{t_1}^{t_2} V dt \quad (2.3)$$

$$L = \sum_{n=1}^N V_n * t_n \quad (2.4)$$

Where:

$V_n$  is the relative ageing rate during interval  $n$ , according to Equation 2.1 or 2.2;

$t_n$  is the  $n$ th time interval ;

$n$  is the number of each time interval;

$N$  is the total number of intervals during the period considered;

## 2.5 Determination of Temperatures

Since mid-1980's that the use of fiber optics in monitoring has been becoming a more popular practice in power transformers, [1], [13], [14], [15], [16], [17], [18], [19].

This technology offers an opportunity for direct measurement of temperatures without any detrimental effect in the dielectric integrity of the transformers, [17]. Traditionally, the temperature measurements are made with the application of a thermal image device (WTI - winding temperature indicator), Figure 2.1, [1].

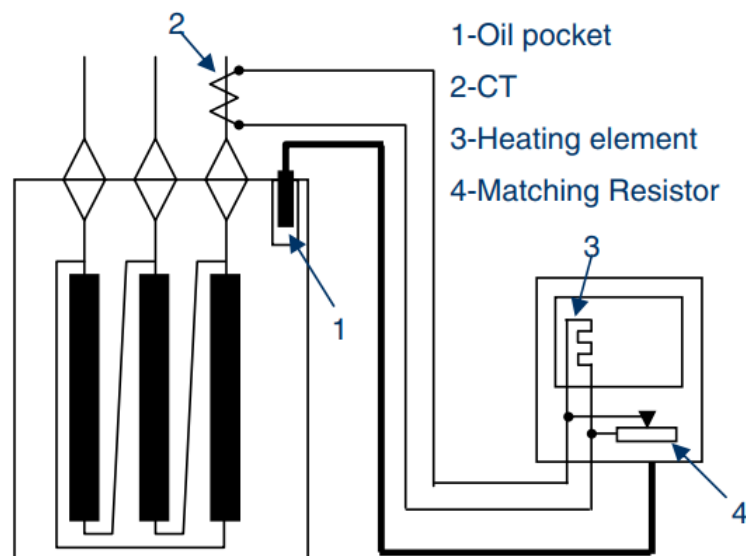


Figure 2.1: WTI - Winding Temperature Indicator, [1]

A thermocouple sensor is immersed in the top oil in the tank, i.e. oil pocket. A proportion of load carried by the heating element is adjusted by the matching resistance to obtain the appropriate “image” of the hotspot temperature. The top-oil to hotspot temperature gradient, obtained during heat-run test, is added to the top-oil temperature reading and the thermal image device copies the temperature of the hottest spot of the winding.

In transient state this indirect method can cause errors, [4], which differs from direct measurement using fiber optic probes, which returns a value much closer to reality. Although the temperature value is more accurate, it is very difficult to know where exactly is the hot spot located, since there is a big thermal dispersion, even though local losses densities and oil circulation speeds are calculated, [20]. Thus, a minimum number of probes is required to ensure a reasonable margin of error for the hot-spot temperature measurement (in practice within the interval  $[-3,0]$  °C from the hottest spot temperature), [7]. Based on results from measurements of hot-spot temperatures from tested power transformers, it has been noticed that the hot-spot temperature rise over top-oil temperature caused by load changes is a function depending on time as well as the transformer loading, [4].

This has shown that the proposed dynamic winding hot-spot calculation methods in the loading guides, [21] and [22], yield significantly low values during transients, especially in the case of a short-term emergency loading. Other problems were also pointed such as non equivalent time constants as the ones proposed by the loading guides, as well as other inconsistencies related to the suggested model. In order to overcome these obstacles, several authors over the years have been suggesting new procedures for calculating the hot-spot temperature of windings for load changes. In the loading guide IEC 60076-7, [3], a simple thermal diagram is assumed, Figure 2.2, to represent a much more complex distribution by making a set of assumptions referred in section 8.1.2 on the loading guide IEC 60076-7, [3].

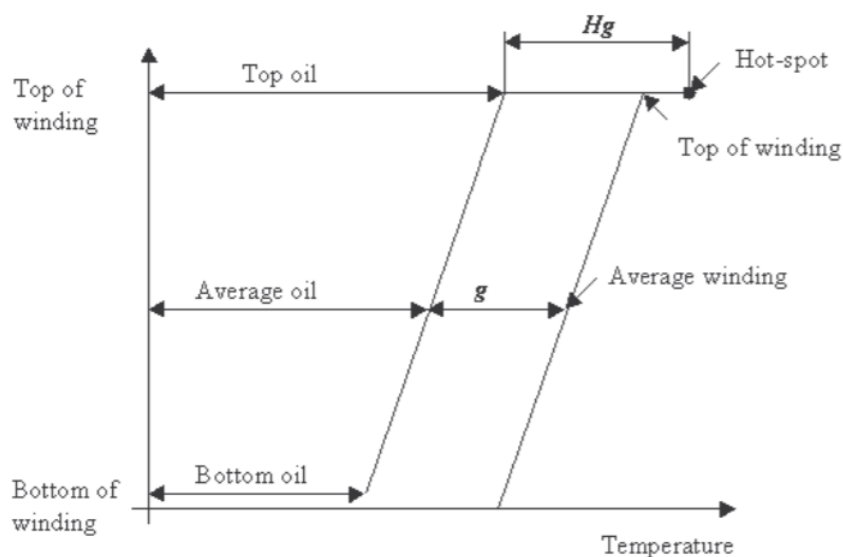


Figure 2.2: Thermal Diagram, [2]

A thermal model is proposed where the variation of the hot-spot temperature of the windings relative to the top-oil temperature after changing the load applied is defined by exponential functions with constant parameters. This model only depends on data from a heat test run, [15], [23], [24].

However, this new approach has caused a lot of technical hitches, due to an unclear knowledge about when and why the exponential method should be used instead of or the differential method and vice versa. D. Susa and H. Nordman in [4] try to clarify the application of this new thermal model.

## 2.6 Differential equations solution

The heat transfer differential equations are represented in block diagram form in Figure 2.3.

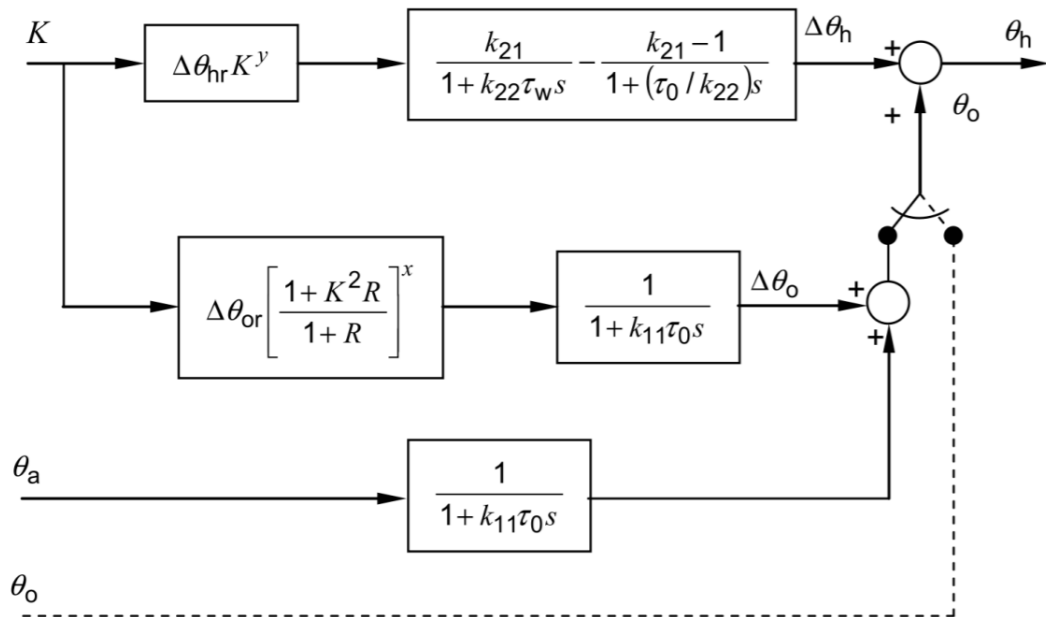


Figure 2.3: Block diagram representation of the differential equations, [3]

In Figure 2.3, the second block in the uppermost path represents the hot-spot rise dynamics. The first term (with numerator  $k_{21}$ ) represents the fundamental hot-spot temperature rise, before the effect of changing oil flow past the hot-spot is taken into account. The second term with numerator  $k_{21} - 1$ ) represents the varying rate of oil flow past the hot-spot, a phenomenon which changes much more slowly. The combined effect of these two terms is to high peak in the hot-spot temperature rise, very soon after the sudden load change.

The mathematical interpretation of the blocks in Figure 2.3 is given as follows:

The differential equation for top-oil temperature is given by:

$$\left[ \frac{1+K^2.R}{1+R} \right]^x . (\Delta\theta_{or}) = k_{11} . \tau_o . \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (2.5)$$

Where:

$K$  is the Load factor;

$R$  is the ratio of load losses at rated current to no-load losses at rated voltage;

$x$  is the oil exponent;

$\Delta\theta_{or}$  is the top-oil temperature rise in steady state at rated losses;

$k_{11}$  is a thermal model constant;

$\tau_o$  is the oil time constant;

$\theta_o$  is the top-oil temperature at the load considered;

$\theta_a$  is the ambient temperature;

The differential equation for hot-spot temperature rise can be solved by the sum of two differential equation solutions, where:

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \quad (2.6)$$

The two equations are:

$$k_{21} . K^y . (\Delta\theta_{hr}) = k_{22} . \tau_w . \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \quad (2.7)$$

and

$$(k_{21} - 1) . K^y . (\Delta\theta_{hr}) = (\tau_o / k_{22}) . \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \quad (2.8)$$

Where:

$k_{21}$  is a thermal model constant;

$K$  is the Load factor;

$y$  is the winding exponent;

$\Delta\theta_{hr}$  is the hot-spot-to-top-oil gradient at rated current;

$k_{22}$  is a thermal model constant;

$\tau_w$  is the winding time constant;

$\tau_o$  is the oil time constant;

The final equation for the hot-spot temperature is given by:

$$\theta_h = \theta_o - \Delta\theta_h \quad (2.9)$$

Where:

$\theta_o$  is the top-oil temperature at the load considered;

$\Delta\theta_h$  is the hot-spot-to-top-oil gradient at the load considered;

## 2.7 Exponential equations solution

According to the IEC 60076-7 loading guide, [3], the hot-spot temperature  $\theta_h(t)$  is equal to the sum of 3 components: the ambient temperature,  $\theta_a(t)$ , the top-oil rise in the tank,  $\Delta\theta_{oi}(t)$ , and the temperature difference between the hot-spot and top-oil in the tank.

The top-oil temperature increase to a level corresponding to a load factor of  $K$  is given by:

$$\theta_o(t) = \theta_a + \Delta\theta_{oi} + (\Delta\theta_{or} * [\frac{1+R*K^2}{1+R}]^x - \Delta\theta_{oi}) * (1 - e^{(-t)/(k_{11}*\tau_o)}) \quad (2.10)$$

Correspondingly, The top-oil temperature decrease to a level corresponding to a load factor of  $K$  is given by:

$$\theta_o(t) = \theta_a + \Delta\theta_{or} * [\frac{1+R*K^2}{1+R}]^x + (\Delta\theta_{oi} - \Delta\theta_{or} * [\frac{1+R*K^2}{1+R}]^x) * (e^{(-t)/(k_{11}*\tau_o)}) \quad (2.11)$$

Where:

$\theta_a$  is the ambient temperature;

$\Delta\theta_{oi}$  is the top-oil temperature rise at start;

$\Delta\theta_{or}$  is the top-oil temperature rise in steady state at rated losses;

$R$  is the ratio of load losses at rated current to no-load losses at rated voltage;

$K$  is the Load factor;

$x$  is the oil exponent;

$t$  is the time variable;

$k_{11}$  is a thermal model constant;

$\tau_o$  is the oil time constant;

The hot-spot to top-oil gradient increase to a level corresponding to a load factor of  $K$  is given by:

$$\Delta\theta_h(t) = \Delta\theta_{h1}(t) - \Delta\theta_{h2}(t) \quad (2.12)$$

where two gradients are:

$$\Delta\theta_{h1}(t) = \Delta\theta_{h1i} + (k_{21} * H * g_r * K^y - \Delta\theta_{h1i}) * (1 - e^{(-t)/(k_{22} * \tau_w)}) \quad (2.13)$$

and

$$\Delta\theta_{h2}(t) = \Delta\theta_{h2i} + ((k_{21} - 1) * H * g_r * K^y - \Delta\theta_{h2i}) * (1 - e^{(-t)/(\tau_o/k_{22})}) \quad (2.14)$$

Correspondingly, The hot-spot to top-oil gradient decrease to a level corresponding to a load factor of  $K$  is given by:

$$\Delta\theta_{h1}(t) = k_{21} * H * g_r * K^y + (\Delta\theta_{h1i} - k_{21} * H * g_r * K^y) * e^{(-t)/(k_{22} * \tau_w)} \quad (2.15)$$

and

$$\Delta\theta_{h2}(t) = (k_{21} - 1) * H * g_r * K^y + (\Delta\theta_{h2i} - (k_{21} - 1) * H * g_r * K^y) * e^{(-t)/(\tau_o/k_{22})} \quad (2.16)$$

Where:

$\Delta\theta_{h_{mhi}}$  is the  $n$ th hot-spot-to-top-oil gradient at start;

$k_{21}$  is a thermal model constant;

$H$  is the hot-spot factor;

$g_r$  is the average-winding-to-average-oil temperature gradient at rated current;

$K$  is the Load factor;

$y$  is the winding exponent;

$t$  is the time variable;

$k_{22}$  is a thermal model constant;

$\tau_w$  is the winding time constant;

$\tau_o$  is the oil time constant;

The final equation for the hot-spot temperature is:

$$\theta_h(t) = \theta_0(t) + \Delta\theta_h(t) \quad (2.17)$$

Characteristic	Small transformers	Medium and large power transformers						
	ONAN	ONAN restricted	ONAN	ONAF restricted	ONAF	OF restricted	OF	OD
Oil exponent $x$	0,8	0,8	0,8	0,8	0,8	1,0	1,0	1,0
Winding exponent $y$	1,6	1,3	1,3	1,3	1,3	1,3	1,3	2,0
Constant $k_{11}$	1,0	0,5	0,5	0,5	0,5	1,0	1,0	1,0
Constant $k_{21}$	1,0	3,0	2,0	3,0	2,0	1,45	1,3	1,0
Constant $k_{22}$	2,0	2,0	2,0	2,0	2,0	1,0	1,0	1,0
Time constant $\tau_o, min$	180	210	210	150	150	90	90	90
Time constant $\tau_w, min$	4	10	10	7	7	7	7	7

Table 2.1: Recommended thermal characteristics for exponential equations, [6]

, [20]

The top-oil exponent  $x$  and the winding exponent  $y$  are given in Table 2.1, [3].

The constants  $k_{11}$ ,  $k_{21}$ ,  $k_{22}$  and the time constants  $\tau_w$  and  $\tau_o$  are transformer specific and can be determined in a prolonged heat-run test during the "no load loss + load loss" period, if the supplied losses and corresponding cooling conditions, for example AN or AF, are kept unchanged from the start until the steady state has been obtained. In this case, it is necessary to ensure that the heat-run test is started when the transformer is approximately at the ambient temperature. It is obvious that  $k_{21}$ ,  $k_{22}$  and  $\tau_w$  can be defined only if the transformer is equipped with fiber optic sensors. If  $\tau_o$  and  $\tau_w$  are not defined in a prolonged heat-run test they can be defined by calculation. In the absence of transformer-specific values, the values in Table 2.1 are recommended, with the drawback of the calculations returning more conservative values in order to obtain a low operating risk.

## 2.8 Difference equations solution

The differential equations are converted to difference equations, making the solution quite simple to apply.

The top-oil temperature is given as follows:

$$D\theta_o = \frac{D_t}{k_{11} \cdot \tau_o} \cdot \left[ \left[ \frac{1+K^2 \cdot R}{1+R} \right]^x \cdot (\Delta\theta_{or}) - [\theta_o - \theta_a] \right] \quad (2.18)$$

Where:

$k_{11}$  is a thermal model constant;

$\tau_o$  is the oil time constant;

$K$  is the Load factor;

$R$  is the ratio of load losses at rated current to no-load losses at rated voltage;

$x$  is the oil exponent;

$\Delta\theta_{or}$  is the top-oil temperature rise in steady state at rated losses;

$\theta_o$  is the top-oil temperature at the load considered;

$\theta_a$  is the ambient temperature;

The  $D$  operator implies a difference in the associated variable that corresponds to each time step  $Dt$ . At each time step, the  $n$ th value of  $D\theta_o$  is calculated from the  $(n-1)$ th value using:

$$\theta_o(n) = \theta_o(n-1) + D\theta_o(n) \quad (2.19)$$

Equations 2.7 and 2.8 become:

$$D\Delta\theta_{h1} = \frac{D_t}{k_{22} \cdot \tau_w} \cdot [k_{21} \cdot \Delta\theta_{hr} \cdot K^y - \Delta\theta_{h1}] \quad (2.20)$$

and

$$D\Delta\theta_{h2} = \frac{D_t}{(1/k_{22}) \cdot \tau_o} \cdot [(k_{21} - 1) \cdot \Delta\theta_{hr} \cdot K^y - \Delta\theta_{h2}] \quad (2.21)$$

Where:

$k_{22}$  is a thermal model constant;

$\tau_w$  is the winding time constant;

$k_{21}$  is a thermal model constant;

$\Delta\theta_{hr}$  is the hot-spot-to-top-oil gradient at rated current;

$K$  is the Load factor;

$y$  is the winding exponent;

$\tau_o$  is the oil time constant;



The  $n$ th values of  $\Delta\theta_{h1}$  and  $\Delta\theta_{h2}$  are calculated in a similar way to Equation 2.19.

The total hot-spot rise at the  $n$ th time step is given by:

$$\Delta\theta_h(n) = \Delta\theta_{h1}(n) - \Delta\theta_{h2}(n) \quad (2.22)$$

The hot-spot temperature at the  $n$ th time step is given by:

$$\theta_h(n) = \theta_o(n) - \Delta\theta_h(n) \quad (2.23)$$

For an accurate solution it is recommended that the time step  $Dt$  should be as small as practicable, no greater than one-half of the smallest time constant in the thermal model. For unknown initial conditions it can be assumed that the system is in steady state, considering the little effect that this has on the final result.

The initial conditions can so be calculated taking the Equations 5, 7 e 8, and setting their time derivatives to zero.

## 2.9 Thermal model constants calculation

The thermal constant  $k_{11}$  should be estimated for the transient top-oil rise temperature curve obtained during the test period with total losses, [4], as follows:

1. Define the function  $f_1(t)$ , which describes the relative increase of the top-oil temperature rise according to the unit of the steady-state value:

$$f_1(t) = (1 - e^{(-t)/k_{11} \cdot \tau_0}) \quad (2.24)$$

2. Obtain measured relative increase of the top-oil temperature rise as per unit of the steady state value,  $Mf_{1j}$ , for the complete test period:

$$Mf_{1j} = \frac{M\theta_{oj} - M\theta_{aj}}{\Delta\theta_{or}} \quad (2.25)$$

3. Perform nonlinear regression by using the guess-error approach (alternatively curve fitting or optimization software also could be used) to find the constant to minimize the sum of squares of differences between  $f_{1j}$  and  $Mf_{1j}$ :

$$\text{minimize: } \sum_{j=1}^N [f_{1j}(z) - Mf_{1j}]^2 \quad (2.26)$$

Where:

$M$  is a measured variable;

$Z$  is a vector whose element is only  $k_{11}$  thermal time constant;

$f_{1j}$  is the relative increase of the top-oil temperature rise as per unit of the steady state value as calculated from Equation 2.24;

$Mf_{1j}$  is the measured relative increase of the top-oil temperature rise as per unit of the steady state value;

$j$  is the index for each time step over the test period with the total losses.

The initial value for the  $k_{11}$  constant is taken from Table 2.1.

The oil time constant value to be set in the function  $f_1(t)$  at the load considered is given by the following Equation, [3]:

$$\tau_o = \frac{C_o \cdot \Delta\theta_{om} \cdot 60}{P} \quad (2.27)$$

Where:

$P$  is the supplied losses in W considered.

The thermal oil capacity  $C_o$  for the ONAN and ONAF cooling modes is:

$$C_o = 0,132.m_A + 0,0882.m_T + 0,4.m_O \quad (2.28)$$

Where:

$m_A$  is the mass of core and coil assembly in kg;

$m_T$  is the mass of the tank and fittings in kg (only those proportions that are in contact with the heated oil shall be used);

$m_O$  is the mass of oil in kg.

For the forced-oil modes either OF or OD, the thermal capacity is:

$$C_o = 0,132.(m_A + m_T) + 0,58.m_O \quad (2.29)$$

The thermal constants  $k_{21}$  and  $k_{22}$  similar to  $k_{11}$  are also obtained from the part of the heat-run test with supplied total loss, [4], as follows:

1. Define function  $f_2(t)$ , which describes the relative increase of the hot-spot-to-top-oil gradient according to the unit of the steady-state value:

$$f_2(t) = k_{21} * (1 - e^{(-t)/(k_{22} * \tau_w)}) - (k_{21} - 1) * (1 - e^{(-t)/(\tau_o/k_{22})}) \quad (2.30)$$

2. Obtain measured relative increase of the hot-spot to top-oil gradient,  $Mf_{2j}$ , as per unit of the steady state value for the complete test period:

$$Mf_{2j} = \frac{M\theta_{hj} - M\theta_{oj}}{\Delta\theta_{hr}} \quad (2.31)$$

3. Perform nonlinear regression by using the guess-error approach (alternatively curve fitting or optimization software also could be used) to find the constant to minimize the sum of squares of differences between  $f_{2j}$  and  $Mf_{2j}$ :

$$\text{minimize: } \sum_{j=1}^N [f_{2j}(z) - Mf_{2j}]^2 \quad (2.32)$$

Where:

$M$  is a measured variable;

$Z$  is a vector whose elements are  $k_{21}$  and  $k_{22}$  constants;

$f_{2j}$  is the relative increase of the hot-spot to top-oil gradient as per unit of the steady state value as calculated from Equation 2.30;

$Mf_{2j}$  is the measured relative increase of the hot-spot to top-oil gradient as per unit of the steady state value;

$j$  is the index for each step over the test period with total losses introduce the following constraint: maximum of  $f_{2j}$  is equal to maximum of  $Mf_{2j}$ .

The initial values for the  $k_{21}$  and  $k_{22}$  constants are taken from Table 2.1.

The winding time constant value to be set in function  $f_2(t)$ , is calculated according to procedure given above, and the winding time constant is as follows [3]:

$$\tau_w = \frac{m_w \cdot c \cdot g}{60 \cdot P_w} \quad (2.33)$$

Where:

$m_w$  is the mass of the winding in kg;

$c$  is the specific heat of the conductor material in Ws/(kg.K) (390 for Cu and 890 for Al);

$g$  is the winding-to-oil gradient in K at the load considered;  $P_w$  is the winding loss in W at the load considered.

An application to a real case, with constant current, [4], shows a comparison between measured hot-spot and top-oil temperatures, calculated by the thermal model of the IEC 60076-7 standard, [3], and the same model with corrected constants. The results obtained from the values of  $k_{11}$ ,  $k_{21}$  and  $k_{22}$  suggested by the IEC 60076-7 standard are quite conservative during the transient period, Figure 2.7 to 2.9. It was also concluded that the results were conservative because the constant  $k_{11}$  was too low for the transformer in question, Figures 2.4 and 2.7.

On the other hand, the corresponding gradients based on the thermal constants  $k_{21}$  and  $k_{22}$  were

close to the measured ones. The values obtained using the corrected constants were closer to the measured values, Figures 2.4 to 2.9.

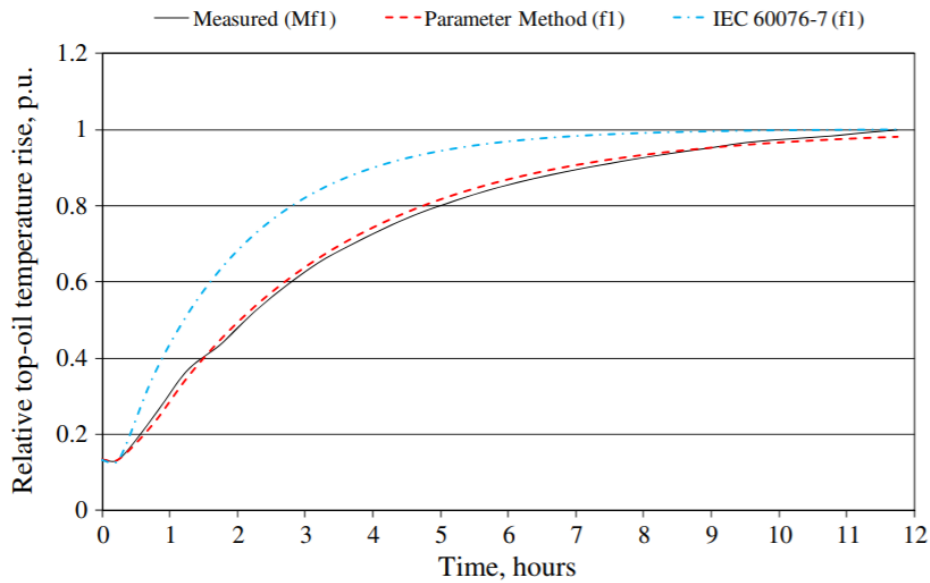


Figure 2.4: Relative top oil temperature rise, [4]

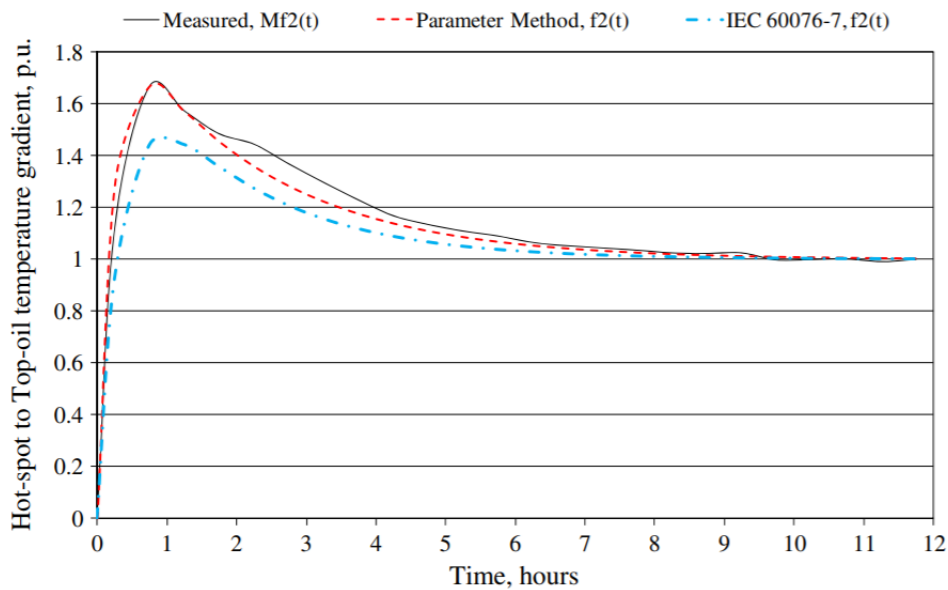


Figure 2.5: Relative hot-spot to top-oil gradient for the low voltage winding, [4]

## 2.10 Transformer Dynamic Thermal Rating

Temperature of transformer insulation system is the basic criterion which limits the transformer loading capabilities. Loading beyond transformer nameplate rating and evaluation of cumulative loss of transformer technical lifetime have been practised since many decades and have

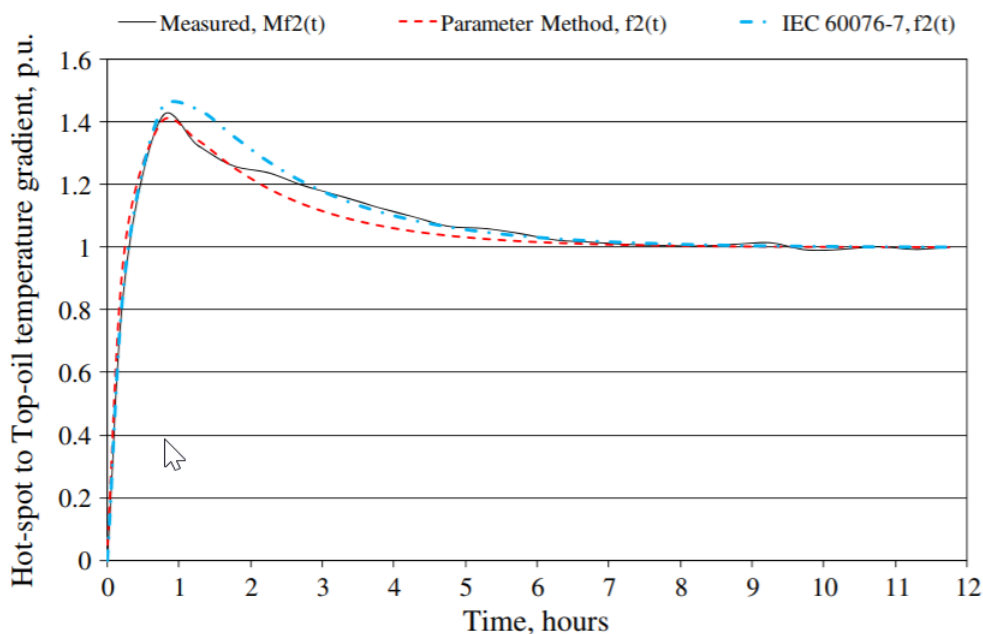


Figure 2.6: Relative hot-spot to top-oil gradient for the high voltage winding, [4]

been described in literature, [15], as well as in current IEC and IEEE Loading Guides, [12], [3]. With development of on-line transformer monitoring applications and inclusion of dynamic thermal models, real-time loading and rating of transformers by hotspot temperature rather than nominal current is viable, also known as transformer Dynamic Thermal Rating (DTR). Transformer DTR offers network operators the opportunity to take full advantage of the transformer thermal performance enabling the safe overloading and keeping the transformer lifetime consumption under control. Dynamic Thermal Model (DTM) enables prediction (calculation) of the transformer hotspot temperature from the measured ambient temperature, cooling and load profiles. Transformer DTR evaluation on the other hand, represents a reversed DTM process, i.e. determination of the load factor limit (kcDTR) that allows transformer operation below the chosen hotspot temperature limit. DTR can be utilized for various purposes and conditions, as shown in Table 2.2.

To predict the impact of transformer loading on its lifetime expectancy, it is crucial to understand the basis of the insulation system ageing process. Ageing of transformer is a complex, time-integrated function of temperature, moisture, acidity and oxygen content of paper-oil insulation system. Hotspot temperature, as the only variable in this function that is typically monitored

Dynamic thermal rating type	Load factor limit criterion
Normal cyclic loading (Normal life expectancy loading)	Hotspot temperature limit
Planned loading beyond nameplate	Daily Loss-of-life (LOL)
Long time emergency loading	LOL, bubbling inception temperature
Short time emergency loading	Bubbling inception temperature

Table 2.2: Transformer dynamic thermal rating types with criteria for the load factor limit, [7]

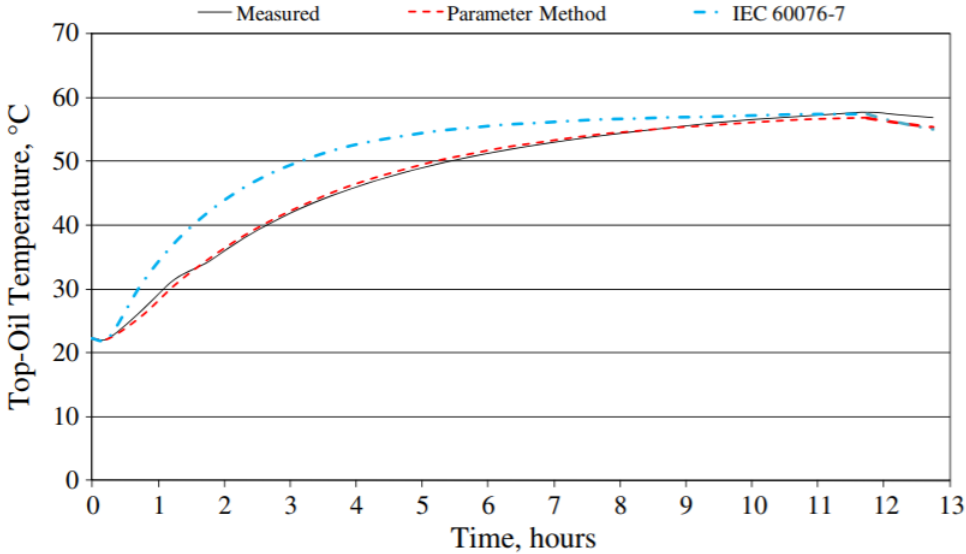


Figure 2.7: Top-oil temperature at varying load, [4]

and indirectly controlled through the cooling system settings, thus plays a central role in assessment of the transformer dynamic thermal rating. Nevertheless the impact of other ageing factors, especially moisture and oxygen, can have a distinct impact on insulation ageing and should thus not be neglected in the thermal rating evaluations, [25].

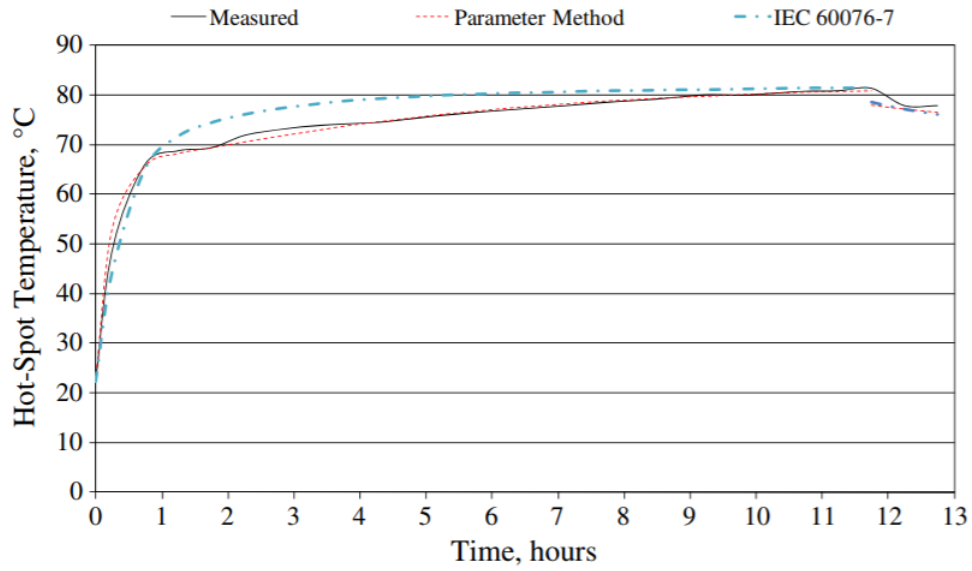


Figure 2.8: Hot-spot temperature low voltage winding, [4]

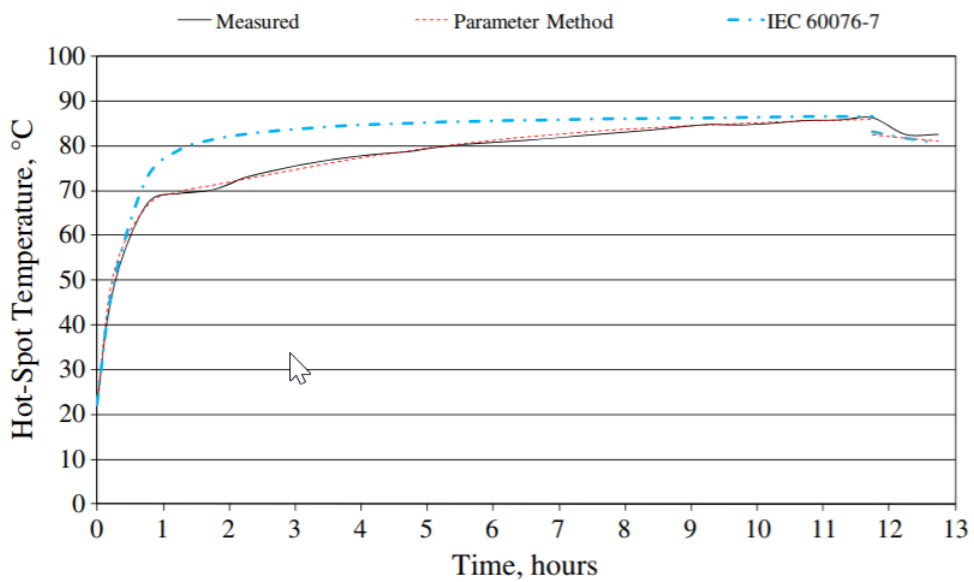


Figure 2.9: Hot-spot temperature high voltage winding, [4]





## Chapter 3

# Solution Development

### 3.1 DTR Structure

The overload capacity determination is based on 3 main sets of inputs: environmental and operational (loading) conditions, transformer insulation system condition and its dynamic thermal model (DTM) parameters, [26].

Environmental and operational (loading) conditions are defined by ambient temperature, wind velocity, sun radiation and loading profiles, which can be measured and predicted rather unambiguously.

The transformer insulation system condition quantify the transformer health level, by defining the DTR temperature limits that must be adjusted throughout the transformer lifetime in order to avoid damages due to a wrong parameterization of the transformer operational behavior. The maximum operational hot-spot temperature is limited by the bubbling inception temperature which decreases with increasing concentration of moisture in the insulation system. The formation of gas bubbles can instantly reduce the dielectric strength of insulation system and can cause a dielectric breakdown in a transformer. The operational hot-spot limit temperature value is adjusted to a value that ensures safe transformer operation. At a 0,5% moisture in the solid insulation, the bubble evolution temperature is above 200C. At a 2% moisture, which corresponds to an aged cellulose insulated transformer, the bubbling inception temperature is above 140C. The conventional hot-spot temperature reference value for a normal transformer life expectancy is defined for a new, degassed and dried transformer with low-oxygen concentration (e.g. 118°C in the IEC standard [27]). In an actual operating transformer, the levels of moisture and oxygen in the insulation system are slowly rising due to ingress of moisture and oxygen from the environment, as well as due to hydrolytic thermal degradation process in the cellulose-oil insulation system. In order to retain an equivalent normal transformer life expectancy and relative ageing rate with an aged transformer, the DTR reference ageing hot-spot temperature value needs to be adjusted accordingly, taking into account the impact of insulation ageing acceleration factors.

The last dependency are the dynamic thermal model parameters, which are the main components of the bridge between the input data and the output variables. These are responsible for the pa-

parameterization of the transformers, constituting one of the most important aspects of the whole algorithm, since they model the transformer response to load changes and temperature variations.

## 3.2 Algorithm

The solution is divided into two parts. One taking the intended load factor as input and returning the maximum time that is possible to operate under such conditions, regarding the maximum temperatures defined by the manufacturer. The second part is the opposite of the former one, using the intended time of operation under overload as input and returning the maximum load factor possible.

The architecture of the algorithm for the first part is given by the following steps, [A.1](#) and [A.2](#):

- Collection of initial values
- Intended Load factor read
- Iteration of temperatures by the Difference Method
- Evaluation of Emergency mode
- Return of possible overload time

The collection of the initial values takes the ambient and top oil temperatures at the moment, the transformer thermal constants and transformer thermal limits.

The intended Load Factor is read from the user interface and normalized if outside the limits of  $[0, 2]$ .

The iteration of the temperatures is made for each time step, following the steps of the Difference Method. After each iteration the top-oil and hot-spot temperature are compared to the maximum value accepted until at least one of them exceeds the limit, ending the iteration loop and returning the previous time step. The first iteration is made for a duration of five times the greater time constant, where it is supposed that the temperature curve has reached steady state, and for the temperature limits of long time emergency.

If the returned possible time is less or equal to 30 minutes the iteration loop is run again for the short time emergency temperature limits and a duration of 30 minutes.

The architecture of the algorithm for the second part is given by the following steps, [A.3](#) and [A.4](#):

- Collection of initial values
- Intended overload time read
- Evaluation of Emergency mode
- Load Factor evaluation and iteration of temperatures by the Difference Method

- Return of possible Load factor

The procedures are similar to the first part, but taking as input the intended overload time. The first iteration is made with the maximum load factor,  $k = 2$ , and the intended duration. The temperature limits are choosed according to the intended duration of the overload. In each iteration, if either the top-oil or hot-spot temperatures reach the maximum values before the entire intended duration, or a specific sensitivity degree for  $k$  is not met, the value of  $k$  is iterated and the temperature simulation loop run again with the new load factor. This new value is achieved by dividing the load factor interval in half. For example, the initial interval is  $[0, 2]$ , which leads to the new value being  $k = 1$ . If in the next iteration the load factor fulfills the temperature requirements, the new interval will be  $[1, 2]$ , and the new value  $k = 1,5$ . If it doesn't fulfill the requirements, the interval will be  $[0, 1]$ , and the new value  $k = 0,5$ . The sensitivity degree of  $k$  is the width of the load factor range and is set to be less or equal to 0,001.

During all the iterations of either the first and second part, if the transformer has more than one cooling method, when the change of stage temperature is reached, the thermal parameters of the transformer are switched for the successive calculations.

In order to approximate the simulation of the evolution of the temperatures in the transformer to reality, it was considered the switching of the cooling stages that occurs in a large number of power transformers. For this, it is necessary to make the parametrization of the transformer for each refrigeration regime in order to model it as best as possible, performing separate heat run tests keeping the cooling method unchanged throughout each one.

The implementation of the algorithm is made using Excel to store and calculate all the data and Visual Basic for Applications to handle all the logic and the user interface, Figure 3.1.

### 3.3 Data

The data for validation of the overload capacity model is provided by previous heat run tests made by an experimental station, on a 15.000KVA ODAF Power Transformer equipped with optical fibers sensors throughout the transformer.

The three heat run tests were made with the following load factors: 1.0, 1.2 and 1.4 pu. All the initial conditions were the same with regard to the cooling mode of the transformer.

It's visible that, because of the test beginning with a cold start, the oil flow in the initial stages isn't behaving normally, as so, the temperatures rises aren't responding as quick as if the oil had his normal operating viscosity, Figures 4.1, 4.3 and 4.5.

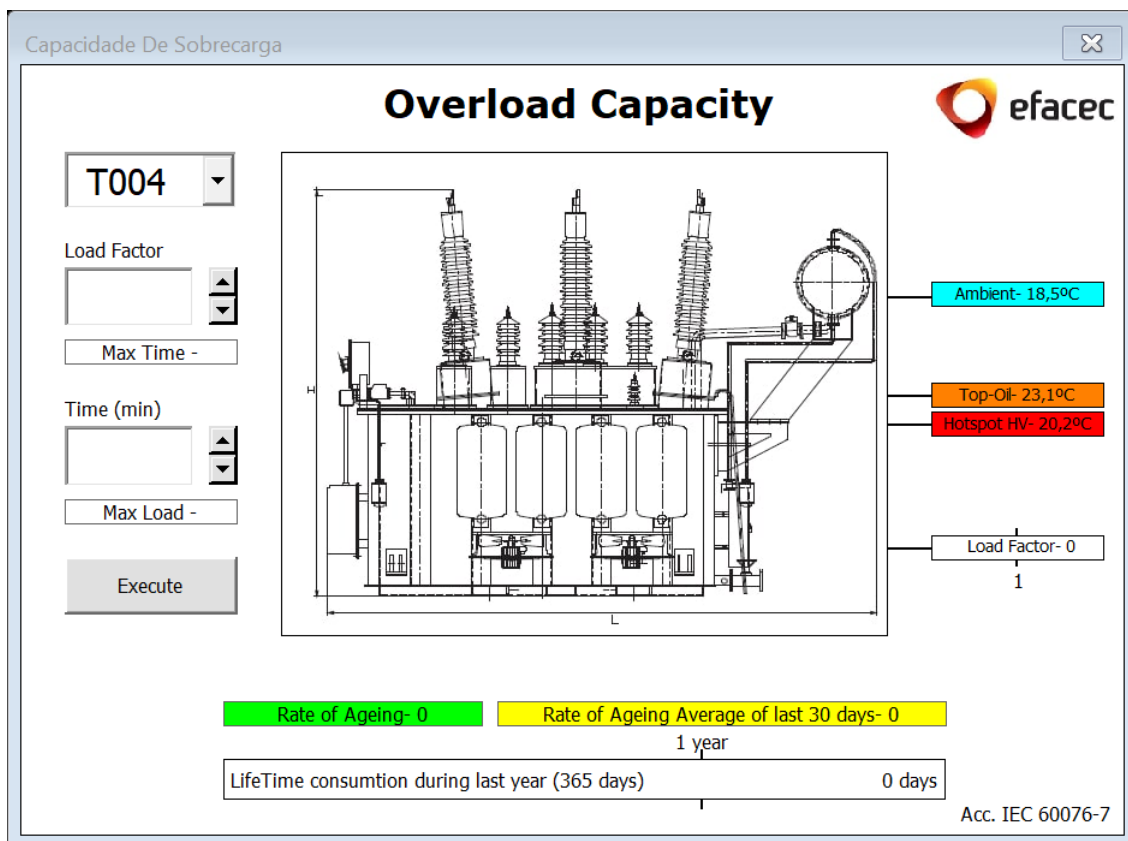


Figure 3.1: User Interface

### 3.4 Solution implementation

The implementation of the algorithm is made by applying the difference model, which the model is based on, to the given input data. If the difference model can correctly model the thermal evolution of the transformer, then the algorithm will make the correct calculations for the maximum overload factor and overload time.

The fact that the data available for analysis not being ideal for this purpose constitutes a major problem in validating the model, starting with the lack of knowledge about the dynamic thermal parameters referring to the transformer, as the cold start, which the thermal model proposed by the international standard handles poorly, this due to not taking into account the high viscosity of the oil when energising a transformer where there was no prior oil circulation. In order to bypass this, in the simulation, the interval referring to the beginning of the oil circulation is set to the measured values.

Due to the absence of the transformer parameters obtained experimentally, a non linear regression is made using the data available for analyses from the heat run test with load factor 1,2pu, in order to ensure that the parameters are the closest to the real ones as much as possible. Despite this solution to extrapolate the thermal model parameters, the short intervals of the data narrows, to a certain extent, the degree of certainty obtained using this method.

## 3.5 Considerations

The algorithm is currently using the ambient temperature at the starting moment of simulation for the entire duration. This is not optimal, justified by the impact that the ambient temperature has on the dynamic thermal model as well as by the big variation that the ambient temperature can have depending on the time of the day as well on the region of the world. Using data from local weather stations or even from a weather station in the substation itself is a benefit in the way of providing the most accurate data possible to the algorithm.

The overload factor taken into consideration is the maximum from the beginning, resembling a step function. This can be improved by applying prior knowledge of the overload, if it has several stages of overload.



# Chapter 4

## Results

From the application of the difference method to the data from the three heat run tests made previously, together with the thermal parameters from the non linear extrapolation, Table 4.1, a simulation of the dynamic behaviour of the transformer is made. Figures 4.1, 4.3 and 4.5 represent the comparison between the calculated and measured temperature values. Figures 4.2, 4.4 and 4.6 represent the error between the calculated and measured values.

The extrapolated parameters in Table 4.1 deviate considerably from those suggested by the standard, [3], in Table 2.1, mainly the constants  $k_{11}$  and  $k_{22}$ .

$\Delta\theta_{or}$	$\Delta\theta_{hr}$	$\tau_o$	$\tau_w$	$R$	$x$	$y$	$k_{11}$	$k_{21}$	$k_2$
20.16	32.39	90	7	7	0.65	1.47	0.35	1.23	1.87

Table 4.1: Thermal parameter from non-linear regression

Figure 4.1 shows the greatest deviation from the calculated values to the measured ones of the three, tending to a shift of the top-oil temperature from  $-5^\circ\text{C}$  and hot-spot from  $-4^\circ\text{C}$ .

Figure 4.3 as expected shows the smallest deviation since it was the heat run test used for the extrapolation of the thermal parameters. It's visible from Figure 4.4 that the thermal parameters are adjusted for this heat run test since the error has clearly two stages, one were the simulated values are above the real ones, and another were the opposite occurs. This differs from the other two applications of the difference method were the error has a clear tendency, to stabilize the deviations in Figure 4.2 and to have a positive slope in the error curve.

Another difference lies in the disparity between the top-oil error and the hot-spot error, were in Figure 4.4 is almost null, and in the other two simulations is 1 to 3  $^\circ\text{C}$ .

The error plots show the clear difficulty of simulating the transient regime under the test conditions considered. Up to 50 min after the start of the simulation, the error curve shows a large variation of slope as well as reaching considerably high values in comparison with the error values for steady state.

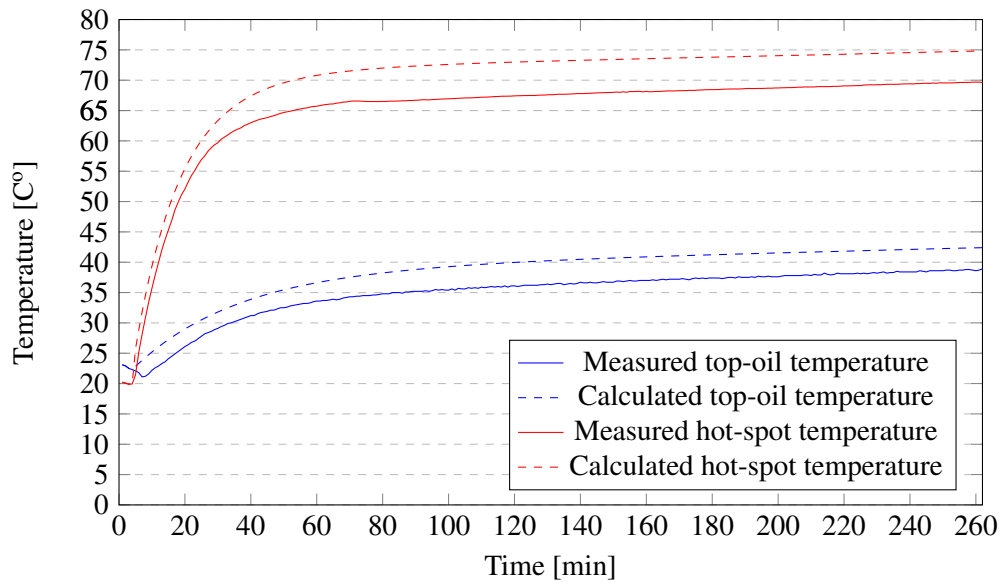


Figure 4.1: Temperatures variation at constant load (1.0 pu)

Applying the thermal parameters to the algorithm, and setting known temperatures as the limit, results in values compatible with the ones given by the difference method for the amount of time needed to reach the limit temperature. The differences are result of the ambient temperature used being considered constant and not a prediction to approximate to the real values, Table 4.2. At low temperatures, a small difference in the amount of time calculated, due to the high slope of the temperature curve, corresponding to the transient regime, can result in a large temperature difference between the simulated and the real ones.

	1pu		1,2pu		1,4pu	
	Algorithm	IEC	Algorithm	IEC	Algorithm	IEC
50°C	11min	12min	7min	8min	6min	7min
70°C	53min	49min	18min	19min	13min	14min
85°C	47min		48min		22min	23min
100°C	53min					51min

Table 4.2: Comparison between Algorithm and Difference method



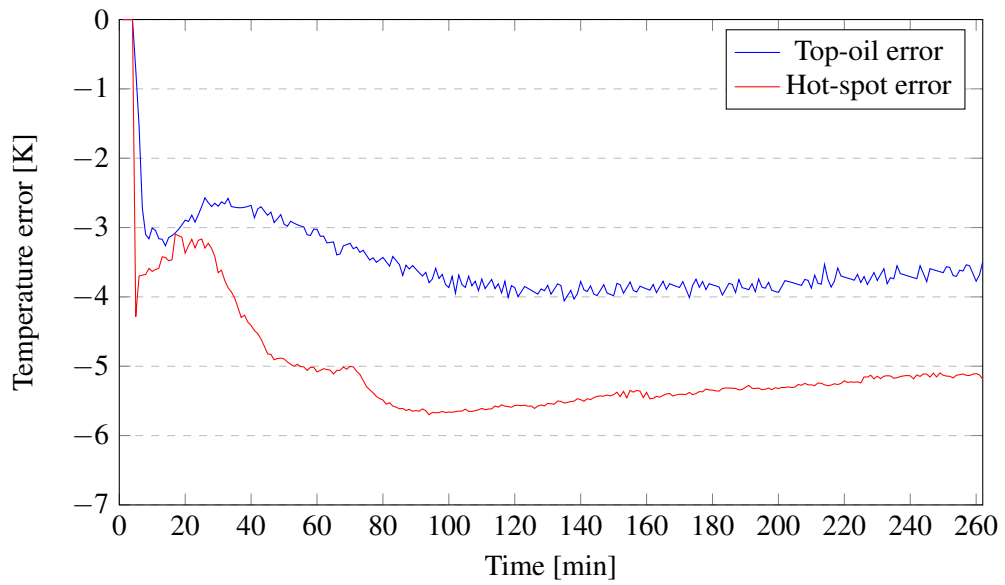


Figure 4.2: Error at constant load (1.0 pu)

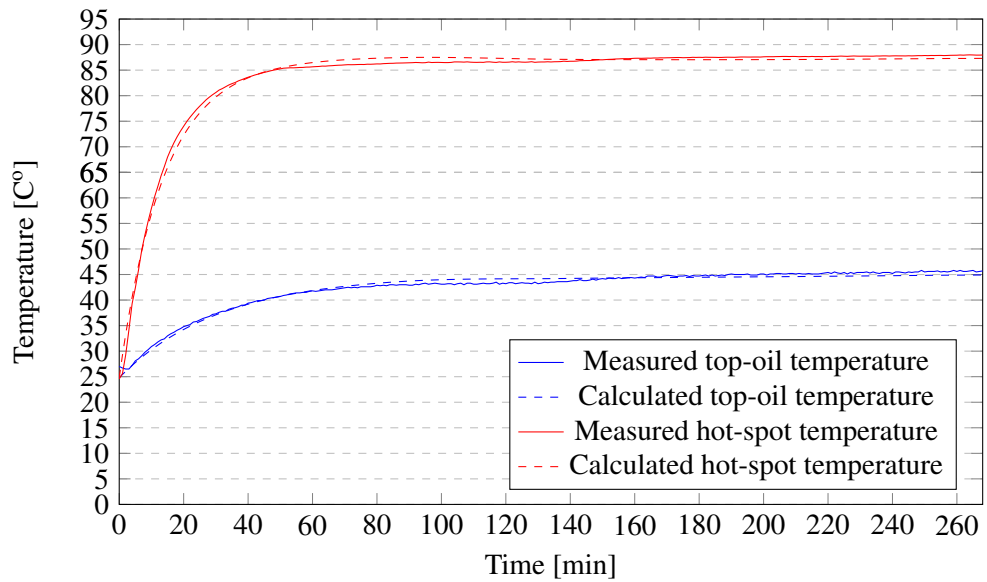


Figure 4.3: Temperatures variation at constant load (1.2 pu)

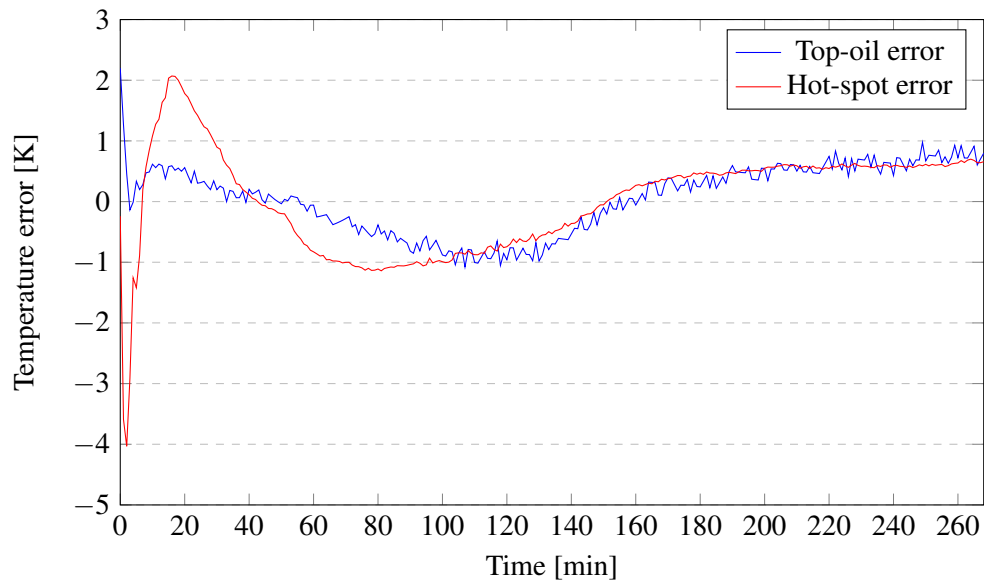


Figure 4.4: Error at constant load (1.2 pu)

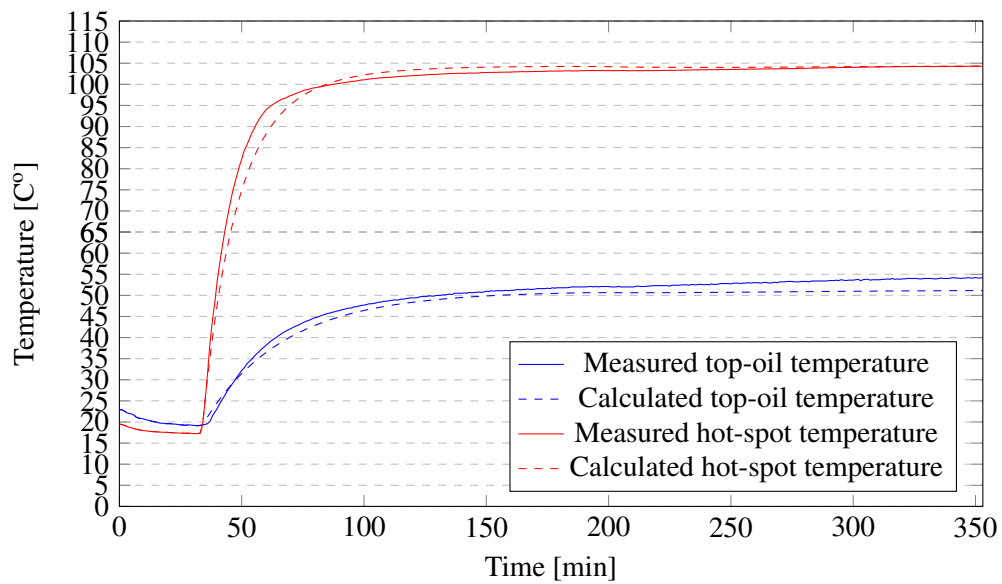


Figure 4.5: Temperatures variation at constant load (1.4 pu)

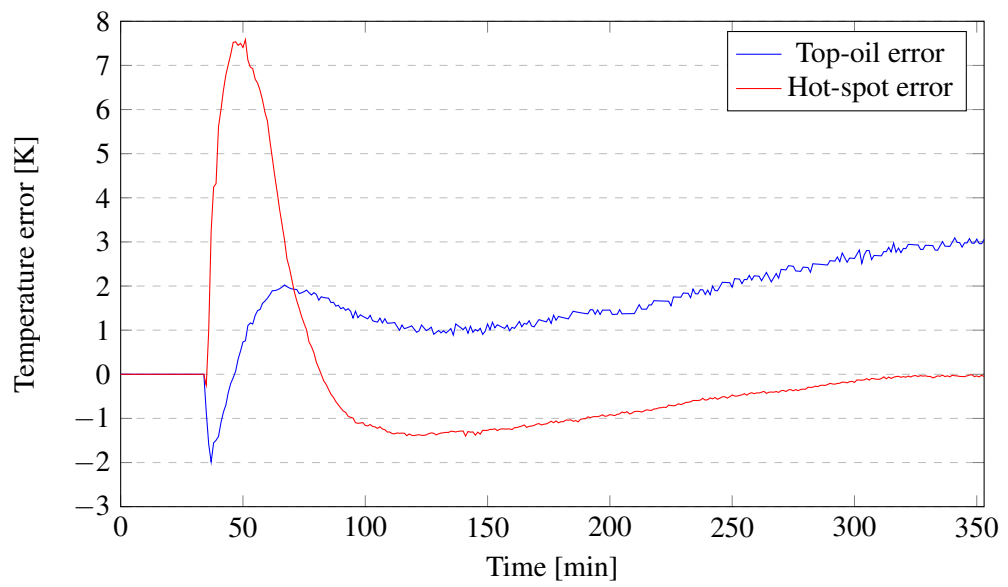


Figure 4.6: Error at constant load (1.4 pu)



## Chapter 5

# Discussion

Through the analyses of the results of the difference method it's possible to affirm that the uncertainty regarding the thermal parameters affects in a significant way the conclusions of the validation. Since the extrapolation of the parameters has the objective to make an approach that minimizes the error, taking into account that the thermal model has its limitations, which means that it can not simulate in a perfect way the measured values, the extrapolation returns parameters that best simulate the heat run test performed with 1.2pu which may differ from the real ones. There is a margin for error justified by the consideration of the algorithm about using the worst case possible for the overload regime, where it is interpreted as a step function with the total duration in the maximum value, not representing the reality, being this unpredictable, makes the simulated temperatures slightly above the real values, thus leaving a safety margin. The value of the overload factor would ideally be the real one, approaching the simulation to reality. This combined with all network assets being managed online and as one, reduces considerably the unpredictability factor on the asset network.

The current state of the parameterization of transformers is only what is required by the customer, ie, what leads to verification of compliance with the steady state heating limits, such as upper oil, medium copper and hot spot.

The dynamic behavior is still not a subject that has aroused relevant interest, but it is assumed that it will change in the next few years, together with fiber optic sensing, for a more preventive monitoring and greater control over the operation of the transformers.

A first step towards the evaluation of the overload capacity can be through the use of the thermal models suggested by international standards, taking into account all the limitations and simplifications considered by them. The models for most cases, when applied with each transformer's specific parameters, makes an approximation to the reality that can be considered acceptable for this initial phase.

Multiple thermal models can also be considered after comparing the differences between them in order to evaluate which one induces the smallest error and the limitations of each one. The model suggested by IEC 60076-7 was used because of its simplicity and EFACEC's prior knowledge of it.

Until now, monitoring overloads is done in a preventive way, where the overload is applied and the temperatures are monitored carefully, ensuring compliance with the maximum limits. This way of operating, in addition to being inefficient, always represents a certain degree of uncertainty regarding the maximum utilization of the network and the way it responds to demand. Operating the network in a more predictive way, based on the simulation of the thermal evolution of the transformer represents a clear value both in the greater control power over the assets and in the energy optimization of the electric network.

## 5.1 Hypothetical situations

The overload of a transformer can be seen as advantageous from various perspectives. Assuming that the customer's goal is the capitalization of the asset, and the price for each MW on normal load is different from the price on an overload regime. This makes it possible to establish a relation between how much is gained by overloading the transformer and the devaluation in terms of cost per unit of remaining life. An example for demonstrating this capitalization of assets with a 100 MVA transformer that is assumed to be worth 2000 k\$ and has a normal life duration of 150.000 hours (17 years) is detailed in Tables 5.1 and 5.2, [8].

Extra loading applied on the transformer	10 MVA
Utilization factor of this extra loading	2000 h/y
Profit margin on transmitted power	8 \$/MWh
Yearly benefit on additional loading	160 k\$/y
Transformer loss of life (2000 h at 120C)	540 0h
Loss of life attributed to overload (5400-2000=3200h)	43 k\$/y
Net value of overloading	117 k\$/y

Table 5.1: Long duration overloading at base energy price, [8]

Extra loading applied on the transformer	30 MVA
Utilization factor of this extra loading	100 h/y
Profit margin on transmitted power	80 \$/MWh
Yearly benefit on additional loading	240 k\$/y
Transformer loss of life (100 h at 140C)	1700 h
Loss of life attributed to overload (1700-100=1600 h)	21 k\$/y
Net value of overloading	219 k\$/y

Table 5.2: Short duration peak load at spot energy price, [8]

Another situation can be to aim to minimize the investment, such as the construction of a new substation or the replacement of assets by more powerful ones, to respond to an increase in energy

demand or contingency situations. Overloading the assets of an existing substation may respond to the energy need and thus delay the investment. The quickness with which the increased energy demand for the overload solution is satisfied is practically immediate, whereas when it comes to the construction of a new substation it is necessary to take into account the time of development and construction, as well as when the solution is the substitution of an asset by a more powerful one, it is necessary to take into account that the substitution will cause an unavailability in the network in certain situations or the overload of other transformers of the substation or group of substations.

Taking as example the critical substation of "Praça Figueira" in Lisbon, Portugal, whose load is described in Table 5.3. It's visible that in a contingency situation during Summer season there is

Name	Praça Figueira	
Supply Voltage	60/10 kV	
Season	Winter	Summer
Natural Load [MVA]	32	35
Installed Power [MVA]	40,0	40,0
Guaranteed Power [MVA]	34,0	31,0
Non-guaranteed Power [MVA]	6,0	9,0
Availability [MVA]	2,2	0,0
Non-guaranteed Load [MVA]	0,0	4,3
Installed Power Non-guaranteed [MVA]	6,0	4,7

Where:

**Natural Load** - is the power required to satisfy the loads of the area of influence of the substation, in MVA;

**Installed Power** - is equal to the sum of the nominal powers of the primary windings of the transformers installed in the substation, in MVA;

**Guaranteed Power** - is the power that the substation can satisfy in case of failure of the higher power transformer and takes into account the possibility of medium voltage, if any, in MVA ('n-1' contingency situation);

**Non-guaranteed Power** - it is the difference between the "Installed Power" and the "Guaranteed Power" in MVA (it represents the power not assured by the substation and its resource by the medium voltage, if it exists, in contingency situation 'n-1');

**Availability** - is the part of the "guaranteed power" that exceeds the "natural load" in MVA (represents the natural load that can be fed, above the existing natural load);

**Non-guaranteed Load** - is the part of the "natural load" that exceeds the "guaranteed power" but is less than "installed power" in MVA (represents the non-powered load in 'n-1' contingency);

**Installed Power non-Guaranteed** - is the part of the "non-guaranteed power" that exceeds the "natural load" in MVA.

Table 5.3: Substation Load information, [9]

a supply gap for the energy demand of about 4,3 MVA. The "Praça Figueira" substation consists of two 20MVA transformers. In case of failure of one during Summer season, if the other one is overloaded with a load factor of 1,215, assuming a hot spot temperature of 131,5°C, this corresponds to an aging acceleration factor of around 8, Equation 2.2. Since the overload is not applied at full time, but instead is only present during peak load from the network, we can relate the data

of the network, Figure 5.1, with the load in the transformer. Being it located in an urban area, it usually follows the profile of the curve of the High Voltage network load diagram. Relating the maximum of the load diagram to the Natural Load from Table 5.3 we obtain the curve in Figure 5.2. Considering the simplification of the temperature rise with the load increase being linear and proportional for the sake of this example, it can be said that, on a contingency situation, in order to fulfill the energy need of the network we can overload the transformer during 61,5% of the day and, if the overload lasts one month, approximately 0.80% of the life of the transformer is spent, compared to 0.28% with hot spot temperature at 110°C, for a 30 year life expectancy, corresponding to an aging factor of 2.87, Figure 5.3.

For a 20MVA 60/15kV transformer, valued at 250.000€, the devaluation under conditions whose hot spot temperature is 110°C is around 690€/month. If the transformer is overloaded following the load diagram, the devaluation is 2000€/month. Even if the summer load profile is applied to a full year on a single transformer from this substation, compared to normal operation, the added devaluation is around 15,5k€ which is less than the difference between the price of what is currently used and a higher-power transformer, 40MVA 60/15kV, valued at 350.000€. Since contingency situations, where the higher-power transformer fails, do not occur frequently, it's a better option to overload the existing operating transformer for the minimum time necessary than to install a higher-power transformer. In the case of this substation and similar ones, which are also located underground and in urban areas, space and accessibility can be limiting factors on upgrading the existing transformers, which increases the overall costs.

The overload of the leftover transformer allows continuous operation of the branch of the power network. Monitoring the transformer specially on this state has a huge importance on managing power distribution maintaining the quality of service.

Another situation where the economic factors do not take part is during a natural disaster or similar, where the energy network is partly conditioned. Here, the main objective is to maintain the continuity of the power supply while keeping the transformer operating conditions safe. Being able to carry out monitoring or even autonomous control of the assets that are operational in the network, through the management of the load distribution over the network makes possible to maintain the network operational despite the adverse conditions.



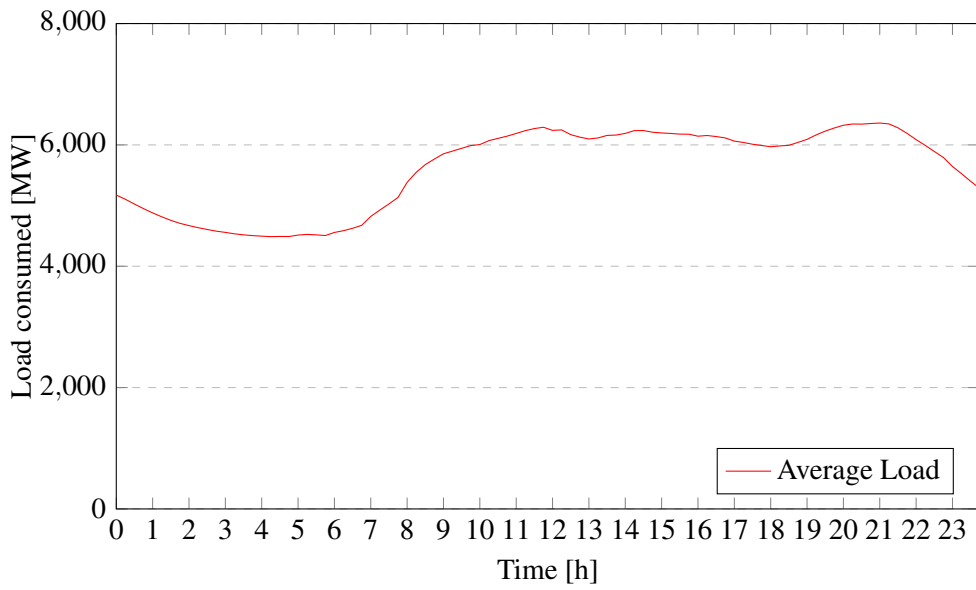


Figure 5.1: Average Load Diagram during 2018 Summer season, [5]

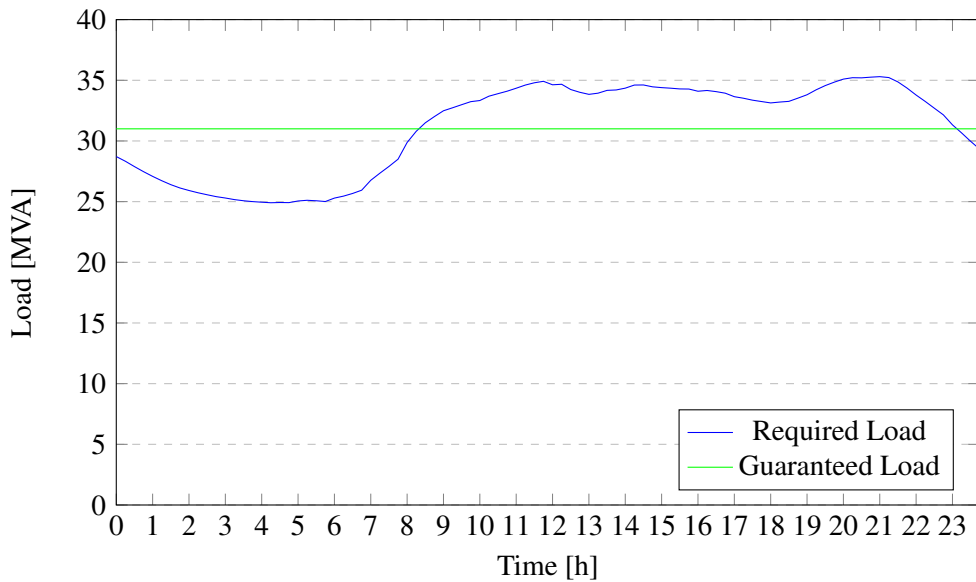


Figure 5.2: Transformer Load Diagram

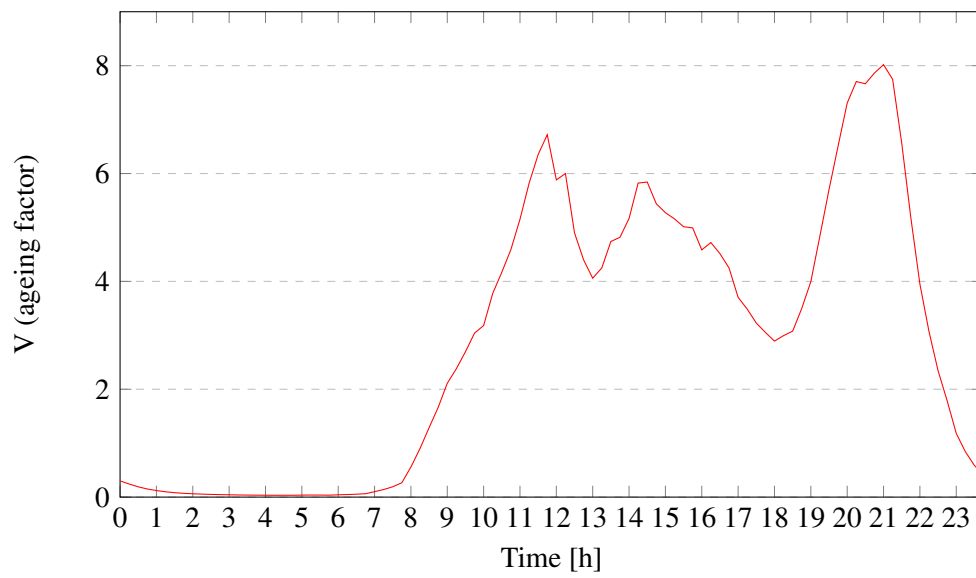


Figure 5.3: Ageing factor

## Chapter 6

### Work to be done

In order to fully verify the algorithm it's necessary to test the difference method with all the conditions that model the transformer as close as possible to reality. To achieve this, it's required to follow the procedures described in Section 2.9 to calculate the thermal model constants.

To correct the external conditions, the ambient temperature used by the algorithm should be provided by another algorithm that returns a temperature prediction based on the region, time of the day, season and preferably supported by data from a local weather station.

The load factor as mentioned, is considered as a step function, this not representing reality in most cases. In planned and long-term emergency overloads it's possible to apply a load factor similar to the curve of the region load diagram, this depending on what kind of area is it, rural, urban or industrial, as well as the time of the day.

For the sake of obtaining the best and most accurate solution, other thermal models should be tested and considered to integrate a hybrid algorithm that brings together two or more thermal models in order to try to correct the gap of the proposed IEC 60076-7 thermal model for low temperatures.



## Chapter 7

# Conclusions

Power transformers constitute one of the most important assets of the power grid, with load cycles tending to become increasingly unpredictable. The option to overload a transformer with full control, in order to promote the best possible management of the load distribution is a service that manufacturers can take advantage to differentiate themselves in the market they are inserted. In this document a review of the state of the art with regard to the IEC 60076-7 proposed thermal model is made, whose principles are used to develop the solution.

An algorithm was developed capable of evaluating the overload capacity of the transformer in the circumstances where it is inserted.

It was applied to a real case where due to the data source and the in use by the industry regarding the parameterization of the transformer it was not possible to reach a solid conclusion of this project in order to guarantee a safe tool with regard to the correct modeling of temperatures. The lack of some of the real transformer thermal parameters constitutes an obstacle to the certification of the reliability of the algorithm with regard to a correspondence with reality. More tests are needed, with inputs that are still unavailable, in order to simulate the operation of a transformer like the similar to one in operation in the power grid, this with all stages of refrigeration as well as with dynamic long-term load profiles.

A set of hypothetical situations were created and evaluated the advantages of overloading a power transformer, to demonstrate the importance of this topic in the exploration of the power network, creating more awareness in manufacturers to this topic with the aim of adding some parameterization practices and creating case studies to contribute to the development of this important area. These hypothetical situations also serve to sensitize customers to a more controlled and less risky overload capacity as a result of the monitoring solutions with which Efacec proposes and continues to develop.

Overloading Power Transformers is not a long-term solution but rather a medium to short, in order to quickly respond to energy demand without compromising the service quality. This overload affects the life expectancy of the transformer with an exponential relation relative to the hot spot temperature, thus being desirable to operate with the lowest temperatures possible.



# Appendix A

## Flowcharts

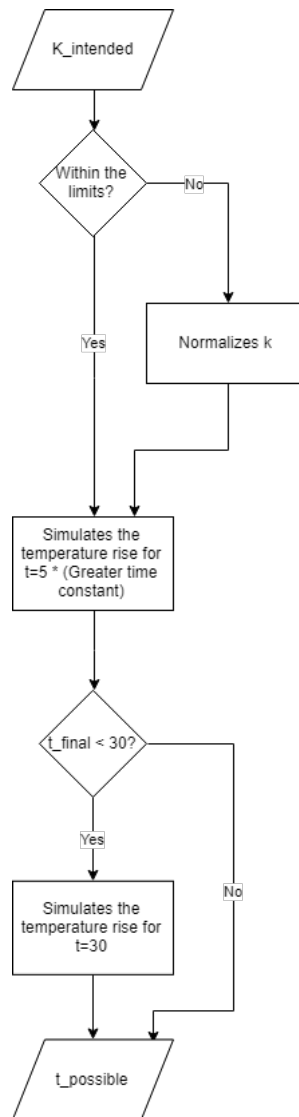


Figure A.1: Possible overload time calculation flowchart

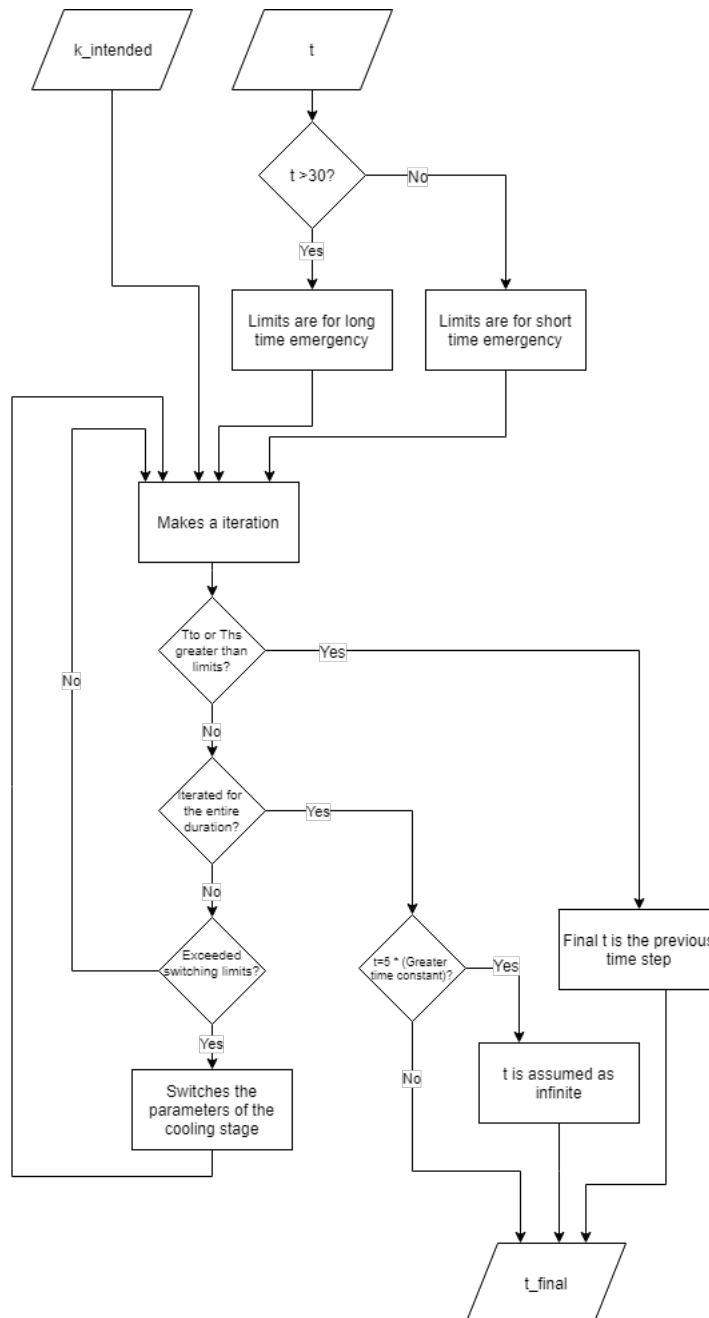


Figure A.2: Temperature simulation for possible overload time calculation flowchart



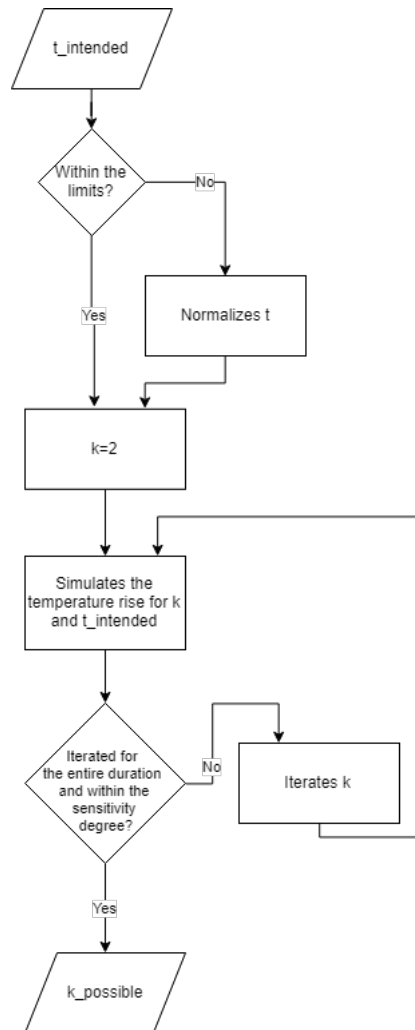


Figure A.3: Possible load factor calculation flowchart

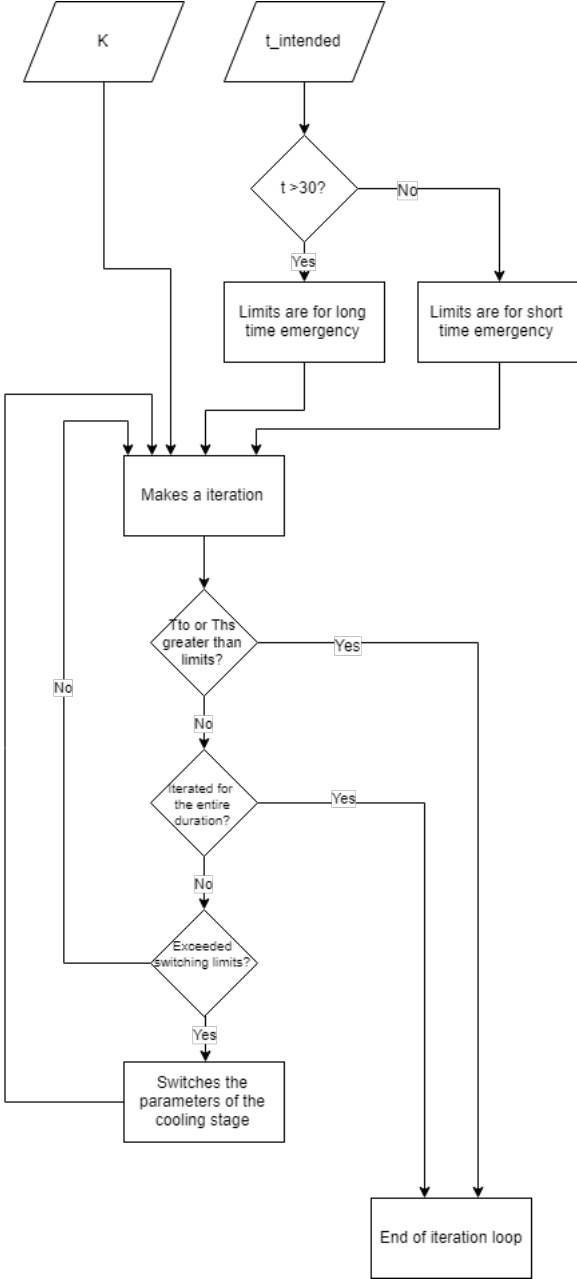


Figure A.4: Temperature simulation for possible load factor calculation flowchart

# Appendix B

## Code

```
1 'Preencher o dropdown menu dos transformadores com as tabs existentes
2 Private Sub UserForm_Initialize()
3     Dim i As Long
4     Me.ComboBox1.Clear
5     For i = 2 To Sheets.Count
6         Me.ComboBox1.AddItem Sheets(i).Name
7     Next
8     Me.ComboBox1.Value = Sheets(2).Name
9
10 Label27.Visible = False
11 Label28.Visible = False
12 Label29.Visible = False
13 Label32.Visible = False
14
15 End Sub
16
17 'Aplicar o valor do SpinButton do K
18 Private Sub SpinButton1_Change()
19
20 TextBox1.Text = SpinButton1.Value / 100
21 End Sub
22
23 'Aplicar o valor do SpinButton do t
24 Private Sub SpinButton2_Change()
25
26 TextBox2.Text = SpinButton2.Value
27 End Sub
28
29 'Iterar pelo mtodo diferencial no tab Simulations
30 Private Sub CommandButton1_Click()
31
32 Dim k, t As Variant
```

```
33
34 Workbooks("Helder_Mockup_UserForm.xlsm").Activate
35 Sheets("Simulations").Activate
36
37 'Modo de clculo manual e screenUpdate para optimizao
38 Application.Calculation = xlCalculationManual
39 Application.ScreenUpdating = False
40
41 Label17.Caption = "Max Time - "
42 Label18.Caption = "Max Load - "
43
44 k = ReadLoad
45
46 t = ReadTime
47
48 Call InitialValues
49
50 Call Calculate(k, t)
51
52 Call AutofitAllUsed
53
54 Application.ScreenUpdating = True
55
56 End Sub
57
58 'Ativa o transformador pretendido na ComboBox1
59 Private Sub ComboBox1_Change()
60
61 Workbooks("Helder_Mockup_UserForm.xlsm").Activate
62 Sheets(ComboBox1.Value).Activate
63
64 Call UpdateHistory
65
66 Call UpdateUserFormInfo
67
68 Call AutofitAllUsed
69
70 End Sub
71
72 'Ajustar as dimenses das colunas da sheet ativa
73 Sub AutofitAllUsed()
74
75 Dim x As Integer
76
77 For x = 1 To ActiveSheet.UsedRange.Columns.Count
```

```
78
79     Columns(x).EntireColumn.AutoFit
80
81 Next x
82
83 End Sub
84
85 'D refresh nos dados do transformador na UserForm
86 Sub UpdateUserFormInfo()
87
88 Dim lRow As Long
89
90 Label17.Caption = "Max Time - "
91 Label18.Caption = "Max Load - "
92 SpinButton1.Value = 0
93 SpinButton2.Value = 0
94 TextBox1.Text = ""
95 TextBox2.Text = ""
96
97
98 'Ultima linha do transformador em questo, coluna A
99 lRow = Cells(Rows.Count, 1).End(xlUp).Row
100
101 Label3.Caption = "Ambient- " & Round(Cells(lRow, 2), 1) & "C"
102 Label11.Caption = "Top-Oil- " & Round(Cells(lRow, 3), 1) & "C"
103 Label2.Caption = "Hotspot HV- " & Round(Cells(lRow, 4), 1) & "C"
104
105 Label24.Caption = "Load Factor- " & Cells(lRow, 5) & ""
106 Label23.Width = (72 * Cells(lRow, 5)) / 2
107
108 Label15.Caption = "Rate of Ageing- " & Round(Cells(lRow, 6), 4) & ""
109 Label16.Caption = "Rate of Ageing Average of last 30 days- " & Round(Cells
    (lRow, 7), 4) & ""
110
111 Label33.Caption = "" & Round(Cells(lRow, 8), 2) & " days"
112 Label11.Width = (300 * Cells(lRow, 8)) / 549
113
114 End Sub
115
116 'Inicializa a sheet de simulao com os dados atualizados do transformador
117 Sub InitialValues()
118
119 Dim lRow As Long
120
121 'Faz clear de clculos passados
```

```
122 Range("A2:O" & Rows.Count).ClearContents
123
124 'Ultima linha do transformador em questo, coluna A
125 lRow = Worksheets(ComboBox1.Value).Cells(Rows.Count, 1).End(xlUp).Row
126
127 'Copia os valores da sheet do transformador correspondentes ao estado
    atual para a primeira linha da sheet Simulations
128 ActiveSheet.Cells(2, 1).Value = 0
129 ActiveSheet.Cells(2, 2).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(lRow, 2).Address & ""
130 ActiveSheet.Cells(2, 3).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(lRow, 5).Address & ""
131 ActiveSheet.Cells(2, 4).Value = "-"
132 ActiveSheet.Cells(2, 5).Value = "-"
133 ActiveSheet.Cells(2, 6).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(lRow, 3).Address & ""
134 ActiveSheet.Cells(2, 7).Value = "-"
135 ActiveSheet.Cells(2, 8).Value = "-"
136 ActiveSheet.Cells(2, 9).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(lRow, 11).Address & ""
137 ActiveSheet.Cells(2, 10).Value = "-"
138 ActiveSheet.Cells(2, 11).Value = "-"
139 ActiveSheet.Cells(2, 12).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(lRow, 14).Address & ""
140 ActiveSheet.Cells(2, 13).Value = "-"
141 ActiveSheet.Cells(2, 14).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(lRow, 4).Address & ""
142 ActiveSheet.Cells(2, 15).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(lRow, 15).Address & ""
143
144 'Valores dos limites
145 ActiveSheet.Cells(2, 31).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(2, 32).Address & ""
146 ActiveSheet.Cells(2, 32).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(2, 33).Address & ""
147 ActiveSheet.Cells(3, 31).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 32).Address & ""
148 ActiveSheet.Cells(3, 32).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 33).Address & ""
149
150
151 End Sub
152
153 'Leitura do factor de carga
154 Public Function ReadLoad() As Variant
```

```
155
156 If (TextBox1.Value <> "") And (IsNumeric(TextBox1.Value)) Then
157
158     If (TextBox1.Value >= 2) Then
159         ReadLoad = 2
160         TextBox1.Value = 2
161         SpinButton1.Value = 200
162     ElseIf (TextBox1.Value < 0) Then
163         ReadLoad = 0
164         TextBox1.Value = 0
165         SpinButton1.Value = 0
166     Else
167         ReadLoad = Round(TextBox1.Value, 3)
168         TextBox1.Value = CDec(TextBox1.Value)
169
170         'Atualiza o valor do SpinButton1, pois pode ter sido inserido
            manualmente
171         SpinButton1.Value = TextBox1.Value * 100
172     End If
173
174 Else
175     ReadLoad = 0
176     TextBox1.Value = 0
177     SpinButton1.Value = 0
178 End If
179
180 End Function
181
182 'Leitura do tempo
183 Public Function ReadTime() As Variant
184
185 If (TextBox2.Value <> "") And (IsNumeric(TextBox2.Value)) Then
186
187     If (TextBox2.Value >= 10000) Then
188         ReadTime = 10000
189         TextBox2.Value = 10000
190         SpinButton2.Value = 10000
191     ElseIf (TextBox2.Value < 1) Then
192         ReadTime = 1
193         TextBox2.Value = 1
194         SpinButton2.Value = 1
195     Else
196         ReadTime = CInt(TextBox2.Value)
197         TextBox2.Value = CInt(TextBox2.Value)
198
```

```
199         'Atualiza o valor do SpinButton2, pois pode ter sido inserido
           manualmente
200         SpinButton2.Value = CInt(TextBox2.Value)
201     End If
202
203 Else
204     ReadTime = 1
205     TextBox2.Value = 1
206     SpinButton2.Value = 1
207 End If
208
209 End Function
210
211 'Faz os clculos para todas as linhas seguintes
212 Sub Simulate(k As Variant, t As Variant, flag As Byte)
213
214 'flag 0 para simulao com base no k e 1 com base no t
215
216 Dim i As Integer
217 Dim HSlim, TOLim As Variant
218
219 Dim a, b As Integer
220 Dim T_up_to, T_down_to, T_up_hs_h, T_down_hs_h, T_up_hs_l, T_down_hs_l As
    Double
221
222 a = 1
223 b = ActiveSheet.Cells(2, 15).Value
224
225 'Determinao de quantos modos de refrigerao tem o transformador
226 If (Worksheets(ComboBox1.Value).Cells(3, 16).Value) <> "" Then
227     a = 2
228 End If
229
230 If (Worksheets(ComboBox1.Value).Cells(7, 16).Value) <> "" Then
231     a = 3
232 End If
233
234 If (Worksheets(ComboBox1.Value).Cells(11, 16).Value) <> "" Then
235     a = 4
236 End If
237
238 T_up_to = Worksheets(ComboBox1.Value).Cells((4 * b) + 3, 16).Value
239 T_down_to = Worksheets(ComboBox1.Value).Cells((4 * b) + 2, 16).Value
240
241 T_up_hs_h = Worksheets(ComboBox1.Value).Cells((4 * b) + 19, 16).Value
```



```
242 T_down_hs_h = Worksheets(ComboBox1.Value).Cells((4 * b) + 18, 16).Value
243
244
245 'Copia os parametros correspondentes fase i para a sheet de simulao
246 ActiveSheet.Cells(3, 16).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 17).Address & ""
247 ActiveSheet.Cells(3, 17).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 18).Address & ""
248 ActiveSheet.Cells(3, 18).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 19).Address & ""
249 ActiveSheet.Cells(3, 19).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 20).Address & ""
250 ActiveSheet.Cells(3, 20).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 21).Address & ""
251 ActiveSheet.Cells(3, 21).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 22).Address & ""
252 ActiveSheet.Cells(3, 22).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 23).Address & ""
253 ActiveSheet.Cells(3, 23).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 24).Address & ""
254 ActiveSheet.Cells(3, 24).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 25).Address & ""
255 ActiveSheet.Cells(3, 25).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 26).Address & ""
256 ActiveSheet.Cells(3, 26).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 27).Address & ""
257 ActiveSheet.Cells(3, 27).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 28).Address & ""
258 ActiveSheet.Cells(3, 28).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(3, 29).Address & ""
259
260
261 'Determinao dos limites do modo de sobrecarga
262 If (t > 30) Then
263     TOLim = ActiveSheet.Cells(2, 32).Value
264     HSLim = ActiveSheet.Cells(3, 32).Value
265 Else
266     TOLim = ActiveSheet.Cells(2, 31).Value
267     HSLim = ActiveSheet.Cells(3, 31).Value
268 End If
269
270 'Barra e percentagem de progresso
271 If (flag = 0) Then
272     Label27.Visible = True
273     Label28.Visible = True
```

```

274 Label29.Visible = True
275 Label32.Caption = "iteration - 1"
276 Label32.Visible = True
277 End If
278
279 For i = 3 To (t + 2)
280
281     'Coluna A
282     ActiveSheet.Cells(i, 1).Value = ActiveSheet.Cells(i - 1, 1).Value + 1
283
284     'Coluna B
285     ActiveSheet.Cells(i, 2).Value = "=" & ActiveSheet.Cells(i - 1, 2).
        Address & ""
286
287     'Coluna C
288     ActiveSheet.Cells(i, 3).Value = k
289
290     'Coluna D
291     ActiveSheet.Cells(i, 4).Value = "=" & ActiveSheet.Cells(i - 1, 6).
        Address & ""
292
293     'Coluna E
294     ActiveSheet.Cells(i, 5).Value = "=" & (" & ActiveSheet.Cells(i, 1).Address
        & "-" & ActiveSheet.Cells(i - 1, 1).Address & ")/($W$3*$R$3))
        *(((1+(" & ActiveSheet.Cells(i, 3).Address & "^2)*$T$3)/(1+$T$3))^
        $U$3)*$P$3-(" & ActiveSheet.Cells(i, 4).Address & "-" & ActiveSheet.
        Cells(i, 2).Address & ")))"
295
296     'Coluna F
297     ActiveSheet.Cells(i, 6).Value = "=" & ActiveSheet.Cells(i, 4).Address &
        "+" & ActiveSheet.Cells(i, 5).Address & ""
298
299     'Coluna G
300     ActiveSheet.Cells(i, 7).Value = "=" & ActiveSheet.Cells(i - 1, 9).
        Address & ""
301
302     'Coluna H
303     ActiveSheet.Cells(i, 8).Value = "=" & (" & ActiveSheet.Cells(i, 1).Address
        & "-" & ActiveSheet.Cells(i - 1, 1).Address & ")/($Y$3*$S$3))*($X$3
        *$Q$3*(" & ActiveSheet.Cells(i, 3).Address & "^$V$3)-" & ActiveSheet
        .Cells(i, 7).Address & ")))"
304
305     'Coluna I
306     ActiveSheet.Cells(i, 9).Value = "=" & ActiveSheet.Cells(i, 7).Address &
        "+" & ActiveSheet.Cells(i, 8).Address & ""

```

```
307
308 'Coluna J
309 ActiveSheet.Cells(i, 10).Value = "=" & ActiveSheet.Cells(i - 1, 12).
    Address & ""
310
311 'Coluna K
312 ActiveSheet.Cells(i, 11).Value = "=" & ActiveSheet.Cells(i, 1).
    Address & "-" & ActiveSheet.Cells(i - 1, 1).Address & ")/((1/$Y$3)*
    $R$3))*(($X$3-1)*$Q$3*( & ActiveSheet.Cells(i, 3).Address & "^$V$3)
    -" & ActiveSheet.Cells(i, 10).Address & ""
313
314 'Coluna L
315 ActiveSheet.Cells(i, 12).Value = "=" & ActiveSheet.Cells(i, 10).Address
    & "+" & ActiveSheet.Cells(i, 11).Address & ""
316
317 'Coluna M
318 ActiveSheet.Cells(i, 13).Value = "=" & ActiveSheet.Cells(i, 9).Address
    & "-" & ActiveSheet.Cells(i, 12).Address & ""
319
320 'Coluna N
321 ActiveSheet.Cells(i, 14).Value = "=" & ActiveSheet.Cells(i, 6).Address
    & "+" & ActiveSheet.Cells(i, 13).Address & ""
322
323 'Coluna O
324 ActiveSheet.Cells(i, 15).Value = b
325
326
327 'Se a ultima temperatura de hotspot for superior ao limite,
328 'atualiza o tempo mximo para o anterior e acaba o loop
329 If (ActiveSheet.Cells(i, 14).Value > HSlim) Or (ActiveSheet.Cells(i, 6)
    .Value > TOLim) Then
330
331     If (flag = 0) Then
332         ActiveSheet.Cells(6, 16).Value = "=" & ActiveSheet.Cells(i - 1,
            1).Address & ""
333     End If
334
335     Label28.Width = 36
336     Label29.Caption = "100%"
337     DoEvents
338     Exit For
339
340 End If
341
342 'Barra e percentagem de progresso
```

```
343 Label28.Width = CInt(36 * ((i - 2)) / (t))
344 Label29.Caption = CInt(100 * ((i - 2) / (t))) & "%"
345 DoEvents
346
347
348 If (a = 2) Then
349     If (b = 0) And ((ActiveSheet.Cells(i, 6).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 14).Value >= T_up_hs_h)) Then
350         b = 1
351         Comute (b)
352     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 6).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 14).Value <= T_down_hs_h)) Then
353         b = 0
354         Comute (b)
355     End If
356 End If
357
358 If (a = 3) Then
359     If (b = 0) And ((ActiveSheet.Cells(i, 6).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 14).Value >= T_up_hs_h)) Then
360         b = 1
361         Comute (b)
362         T_up_to = Worksheets(ComboBox1.Value).Cells(7, 16).Value
363         T_down_to = Worksheets(ComboBox1.Value).Cells(6, 16).Value
364         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(23, 16).Value
365         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(22, 16).Value
366
367     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 6).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 14).Value <= T_down_hs_h)) Then
368
369         b = 0
370         Comute (b)
371         T_up_to = Worksheets(ComboBox1.Value).Cells(3, 16).Value
372         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(19, 16).Value
373
374     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 6).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 14).Value >= T_up_hs_h)) Then
375         b = 2
376         Comute (b)
377         T_down_to = Worksheets(ComboBox1.Value).Cells(10, 16).Value
378         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(26, 16).Value
379     ElseIf (b = 2) And ((ActiveSheet.Cells(i, 6).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 14).Value <= T_down_hs_h)) Then
380         b = 1
381         Comute (b)
```

```
382         T_up_to = Worksheets(ComboBox1.Value).Cells(7, 16).Value
383         T_down_to = Worksheets(ComboBox1.Value).Cells(6, 16).Value
384         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(23, 16).Value
385         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(22, 16).Value
386     End If
387
388 End If
389
390 If (a = 4) Then
391     If (b = 0) And ((ActiveSheet.Cells(i, 6).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 14).Value >= T_up_hs_h)) Then
392         b = 1
393         Comute (b)
394         T_up_to = Worksheets(ComboBox1.Value).Cells(7, 16).Value
395         T_down_to = Worksheets(ComboBox1.Value).Cells(6, 16).Value
396         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(23, 16).Value
397         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(22, 16).Value
398     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 6).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 14).Value <= T_down_hs_h)) Then
399         b = 0
400         Comute (b)
401         T_up_to = Worksheets(ComboBox1.Value).Cells(3, 16).Value
402         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(19, 16).Value
403     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 6).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 14).Value >= T_up_hs_h)) Then
404         b = 2
405         Comute (b)
406         T_up_to = Worksheets(ComboBox1.Value).Cells(11, 16).Value
407         T_down_to = Worksheets(ComboBox1.Value).Cells(10, 16).Value
408         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(27, 16).Value
409         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(22, 16).Value
410     ElseIf (b = 2) And ((ActiveSheet.Cells(i, 6).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 14).Value <= T_down_hs_h)) Then
411         b = 1
412         Comute (b)
413         T_up_to = Worksheets(ComboBox1.Value).Cells(7, 16).Value
414         T_down_to = Worksheets(ComboBox1.Value).Cells(6, 16).Value
415         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(23, 16).Value
416         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(22, 16).Value
417     ElseIf (b = 2) And ((ActiveSheet.Cells(i, 6).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 14).Value >= T_up_hs_h)) Then
418         b = 3
419         Comute (b)
420         T_down_to = Worksheets(ComboBox1.Value).Cells(14, 16).Value
421         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(30, 16).Value
```

```
422     ElseIf (b = 3) And ((ActiveSheet.Cells(i, 6).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 14).Value <= T_down_hs_h)) Then
423         b = 2
424         Comute (b)
425         T_up_to = Worksheets(ComboBox1.Value).Cells(11, 16).Value
426         T_down_to = Worksheets(ComboBox1.Value).Cells(10, 16).Value
427         T_up_hs_h = Worksheets(ComboBox1.Value).Cells(27, 16).Value
428         T_down_hs_h = Worksheets(ComboBox1.Value).Cells(22, 16).Value
429     End If
430 End If
431
432
433 Next i
434
435 If (flag = 0) Then
436     If (t = 750) And (t = i - 3) And (ActiveSheet.Cells(i - 1, 14).Value <=
        HSlim) And (ActiveSheet.Cells(i - 1, 6).Value <= Tolim) Then
437         ActiveSheet.Cells(6, 16).Value = "infinite"
438     End If
439
440     If (t = 30) And (t = i - 3) And (ActiveSheet.Cells(i - 1, 14).Value <=
        HSlim) And (ActiveSheet.Cells(i - 1, 6).Value <= Tolim) Then
441         ActiveSheet.Cells(6, 16).Value = 30
442     End If
443 End If
444
445 End Sub
446
447
448 Sub Calculate(k As Variant, t As Variant)
449
450 'Descobrir tempo pelo mtodo exponncial
451
452 Call Simulate(k, 750, 0)
453
454 If (ActiveSheet.Cells(6, 16).Value <= 30) And (IsNumeric(ActiveSheet.Cells
        (6, 16))) Then
455
456     'Faz clear de clculos passados
457     Range("A3:O" & Rows.Count).ClearContents
458
459     Call Simulate(k, 30, 0)
460 End If
461
462
```

```
463 'Faz clear de clculos passados
464 Range("A3:O" & Rows.Count).ClearContents
465
466 ActiveSheet.Cells(6, 17).Value = LoadFinder(2, t)
467
468
469 'Atualiza os valores mximos de tempo
470 If (IsNumeric(ActiveSheet.Cells(6, 16))) Then
471     Label17.Caption = "Max Time - " & CInt(ActiveSheet.Cells(6, 16)) & "min
        "
472 Else
473     Label17.Caption = "Max Time - infinite"
474 End If
475
476
477
478 'Atualiza os valores mximos de carga
479 If (ActiveSheet.Cells(6, 17).Value <= 2) Then
480     Label18.Caption = "Max Load - " & Round(ActiveSheet.Cells(6, 17), 3) &
        ""
481 Else
482     Label18.Caption = "Max Load - 2"
483 End If
484
485 End Sub
486
487
488 Public Function LoadFinder(load As Variant, t As Variant) As Variant
489
490 Dim min, max As Variant
491 Dim lRow As Long
492 Dim HSlim As Variant
493 Dim a As Integer
494
495 a = 2
496
497 If (t > 30) Then
498     HSlim = ActiveSheet.Cells(3, 32).Value
499 Else
500     HSlim = ActiveSheet.Cells(3, 31).Value
501 End If
502
503 max = t
504 min = 0
505
```

```
506 Call Simulate(load, t, 1)
507
508 'Ultima linha da simulao
509 lRow = Worksheets("Simulations").Cells(Rows.Count, 1).End(xlUp).Row
510
511
512 'If serve para averiguar o valor da carga da parte do top-oil
513 If (ActiveSheet.Cells(lRow, 14).Value > HSlim) Then
514
515
516     Do While (((max - min) > 0.001) Or (ActiveSheet.Cells(lRow, 14).Value >
517         HSlim) Or (lRow <> t + 2))
518
519         Label32.Caption = "iteration - " & a
520         a = a + 1
521
522         If (ActiveSheet.Cells(lRow, 14).Value > HSlim) Then
523             max = load
524             min = min
525             load = max - ((max - min) / 2)
526
527         Else
528             max = max
529             min = load
530             load = max - ((max - min) / 2)
531
532         End If
533
534     'Faz clear de clculos passados
535     Range("A3:O" & Rows.Count).ClearContents
536
537     Call Simulate(load, t, 1)
538
539     'Ultima linha da simulao
540     lRow = Worksheets("Simulations").Cells(Rows.Count, 14).End(xlUp).Row
541
542     If (load < 0.0001) And (lRow = 3) And (ActiveSheet.Cells(lRow, 14).
543         Value > HSlim) Then
544         Exit Do
545     End If
546 Loop
547 End If
548
```



```
549 Label27.Visible = False
550 Label28.Visible = False
551 Label29.Visible = False
552 Label32.Visible = False
553 DoEvents
554
555 LoadFinder = load
556
557 End Function
558
559 Sub UpdateHistory()
560
561 Dim lRow, lRow_calculations As Long
562 Dim i, x As Integer
563 Dim sum As Variant
564 Dim a, b As Integer
565 Dim T_up_to, T_down_to, T_up_hs_h, T_down_hs_h, T_up_hs_l, T_down_hs_l As
    Double
566
567 lRow = Cells(Rows.Count, 1).End(xlUp).Row
568 lRow_calculations = Cells(Rows.Count, 6).End(xlUp).Row
569
570 a = 1
571 b = (Worksheets(ComboBox1.Value).Cells(lRow_calculations, 15).Value)
572
573 'Determinao de quantos modos de refrigerao tem o transformador
574 If (Worksheets(ComboBox1.Value).Cells(3, 16).Value) <> "" Then
575     a = 2
576 End If
577
578 If (Worksheets(ComboBox1.Value).Cells(7, 16).Value) <> "" Then
579     a = 3
580 End If
581
582 If (Worksheets(ComboBox1.Value).Cells(11, 16).Value) <> "" Then
583     a = 4
584 End If
585
586 If (lRow_calculations < lRow) Then
587
588 For i = (lRow_calculations + 1) To (lRow)
589
590     T_up_to = Worksheets(ComboBox1.Value).Cells((4 * b) + 3, 16).Value
591     T_down_to = Worksheets(ComboBox1.Value).Cells((4 * b) + 2, 16).Value
592
```

```

593 T_up_hs_h = Worksheets(ComboBox1.Value).Cells((4 * b) + 19, 16).Value
594 T_down_hs_h = Worksheets(ComboBox1.Value).Cells((4 * b) + 18, 16).Value
595
596 sum = 0
597
598 'Coluna F
599 If (ActiveSheet.Cells(2, 35).Value = True) Then
600 ActiveSheet.Cells(i, 6).Value = "=EXP(((15000)/(110+273))-((15000)/(" &
        ActiveSheet.Cells(i, 4).Address & "+273)))"
601 Else
602 ActiveSheet.Cells(i, 6).Value = "=2^((" & ActiveSheet.Cells(i, 4).
        Address & "-98)/(6))"
603 End If
604
605 For x = 1 To 14400
606     sum = sum + ActiveSheet.Cells(i + 1 - x, 6).Value
607
608     If (ActiveSheet.Cells(i - x, 1).Value = 0) Then
609         x = x + 1
610         Exit For
611     End If
612
613 Next x
614
615 sum = sum / (x - 1)
616
617
618 'Coluna G
619 ActiveSheet.Cells(i, 7).Value = sum
620
621 'Coluna H
622 ActiveSheet.Cells(i, 8).Value = "=" & ActiveSheet.Cells(i - 1, 8).
        Address & "+" & ActiveSheet.Cells(i, 6).Address & "*" & ActiveSheet
        .Cells(i, 1).Address & "-" & ActiveSheet.Cells(i - 1, 1).Address &
        ")/1440"
623
624 'Coluna I
625 ActiveSheet.Cells(i, 9).Value = "=" & ActiveSheet.Cells(i - 1, 11).
        Address & ""
626
627 'Coluna J
628 ActiveSheet.Cells(i, 10).Value = "=(" & ActiveSheet.Cells(i, 1).
        Address & "-" & ActiveSheet.Cells(i - 1, 1).Address & ")/($Z$" & (4
        * b) + 3 & "$T$" & (4 * b) + 3 & ")")*($Y$" & (4 * b) + 3 & "$R$" &

```

```

        (4 * b) + 3 & "*" & ActiveSheet.Cells(i, 5).Address & "^$W$" & (4
        * b) + 3 & "-" & ActiveSheet.Cells(i, 9).Address & ")"
629
630 'Coluna K
631 ActiveSheet.Cells(i, 11).Value = "=" & ActiveSheet.Cells(i, 9).Address
        & "+" & ActiveSheet.Cells(i, 10).Address & ""
632
633 'Coluna L
634 ActiveSheet.Cells(i, 12).Value = "=" & ActiveSheet.Cells(i - 1, 14).
        Address & ""
635
636 'Coluna M
637 ActiveSheet.Cells(i, 13).Value = "(" & ActiveSheet.Cells(i, 1).
        Address & "-" & ActiveSheet.Cells(i - 1, 1).Address & ")/((1/$Z$" &
        (4 * b) + 3 & ")*$$" & (4 * b) + 3 & "))*(($Y$" & (4 * b) + 3 &
        "-1)*R$" & (4 * b) + 3 & "*" & ActiveSheet.Cells(i, 5).Address &
        "^$W$" & (4 * b) + 3 & "-" & ActiveSheet.Cells(i, 12).Address & ")"
        ""
638
639 'Coluna N
640 ActiveSheet.Cells(i, 14).Value = "=" & ActiveSheet.Cells(i, 12).Address
        & "+" & ActiveSheet.Cells(i, 13).Address & ""
641
642 'Coluna O
643 ActiveSheet.Cells(i, 15).Value = b
644
645
646
647 'Comutao de modo de refrigerao
648 If (a = 2) Then
649     If (b = 0) And ((ActiveSheet.Cells(i, 3).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 4).Value >= T_up_hs_h)) Then
650         b = 1
651
652     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 3).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 4).Value <= T_down_hs_h)) Then
653         b = 0
654     End If
655 End If
656
657 If (a = 3) Then
658     If (b = 0) And ((ActiveSheet.Cells(i, 3).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 4).Value >= T_up_hs_h)) Then
659         b = 1
660

```

```
661     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 3).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 4).Value <= T_down_hs_h)) Then
662         b = 0
663
664     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 3).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 4).Value >= T_up_hs_h)) Then
665         b = 2
666
667     ElseIf (b = 2) And ((ActiveSheet.Cells(i, 3).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 4).Value <= T_down_hs_h)) Then
668         b = 1
669     End If
670
671 End If
672
673 If (a = 4) Then
674     If (b = 0) And ((ActiveSheet.Cells(i, 3).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 4).Value >= T_up_hs_h)) Then
675         b = 1
676
677     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 3).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 4).Value <= T_down_hs_h)) Then
678         b = 0
679
680     ElseIf (b = 1) And ((ActiveSheet.Cells(i, 3).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 4).Value >= T_up_hs_h)) Then
681         b = 2
682
683     ElseIf (b = 2) And ((ActiveSheet.Cells(i, 3).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 4).Value <= T_down_hs_h)) Then
684         b = 1
685
686     ElseIf (b = 2) And ((ActiveSheet.Cells(i, 3).Value >= T_up_to) Or (
        ActiveSheet.Cells(i, 4).Value >= T_up_hs_h)) Then
687         b = 3
688
689     ElseIf (b = 3) And ((ActiveSheet.Cells(i, 3).Value <= T_down_to) And (
        ActiveSheet.Cells(i, 4).Value <= T_down_hs_h)) Then
690         b = 2
691     End If
692 End If
693
694
695 Next i
696
```

```
697 End If
698
699 End Sub
700
701
702 Sub Comute(b As Integer)
703
704 Dim i As Integer
705
706 'Linha onde est a fase de refrigeracao pretendida (3, 7, 11 ou 15)
707 i = (4 * b) + 3
708
709 'Copia os parametros correspondentes fase i para a sheet de simulao
710 ActiveSheet.Cells(3, 16).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 17).Address & ""
711 ActiveSheet.Cells(3, 17).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 18).Address & ""
712 ActiveSheet.Cells(3, 18).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 19).Address & ""
713 ActiveSheet.Cells(3, 19).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 20).Address & ""
714 ActiveSheet.Cells(3, 20).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 21).Address & ""
715 ActiveSheet.Cells(3, 21).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 22).Address & ""
716 ActiveSheet.Cells(3, 22).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 23).Address & ""
717 ActiveSheet.Cells(3, 23).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 24).Address & ""
718 ActiveSheet.Cells(3, 24).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 25).Address & ""
719 ActiveSheet.Cells(3, 25).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 26).Address & ""
720 ActiveSheet.Cells(3, 26).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 27).Address & ""
721 ActiveSheet.Cells(3, 27).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 28).Address & ""
722 ActiveSheet.Cells(3, 28).Value = "=" & ComboBox1.Value & "!" & Worksheets(
    ComboBox1.Value).Cells(i, 29).Address & ""
723
724
725 End Sub
```



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