UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF TOP-OIL TEMPERATURE THERMAL MODELS FOR TRANSFORMER

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DEVELOPMENT OF TOP-OIL TEMPERATURE THERMAL MODELS FOR TRANSFORMER

By

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DEVELOPMENT OF TOP-OIL TEMPERATURE THERMAL MODELS FOR TRANSFORMER

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Faculty: Engineering

Hot-Spot Temperature (HST) is defined as the highest temperature inside a transformer and can be determined based on the numerical network thermal model. In this approach, Top-Oil Temperature (TOT) is among the crucial components to obtain reliable HST. Currently, there are two loading guides that utilize the numerical network thermal model in order to obtain the TOT which are IEC 60076-7 and IEEE C57.91-1995. Other types of TOT numerical network thermal model are based on the thermal-electrical analogy method. There are several improvements that can be applied to existing TOT models such as reducing the complexity of the models and increasing the accuracy which is the main motivation of this study. The main aim of this research is to provide alternative approaches to obtain the TOT of transformers. Two TOT thermal models were proposed in this study named as Thermal Model 1 (TM1) and Thermal Model 2 (TM2). These models were developed based on the proposed concept of pathway of energy transfer. . TM1 was developed based on redefinition of nonlinear thermal resistance through approximation of convection coefficient, *h*. Meanwhile, TM2 was developed based on the concept of nonlinearity of thermal resistance of which the oil time constant was embedded in the model in order to improve the accuracy. The performance of the TM1 and TM2 were evaluated based on measured TOT with constant loadings from 7 transformers with either ONAN or ONAF cooling modes. Both TM1 and TM2 were also tested on a transformer with step loading. The performances of TM1 and TM2 were analyzed through comparison with previous Thermal-Electrical (namely as TE1 and TE2), Exponential (IEC 60076-7) and Clause 7 (IEEE C57.91-1995) TOT thermal models. Under constant loading, both TM1 and TM2 perform relatively well compare to TE1 and TE2 models. The performance of TM1 and TM2 are even better than Exponential and Clause 7 models to represent the measured TOT. The highest maximum and Root Mean Square (RMS) errors for TM1 are 6.66 °C and 2.76 °C while TM2 has the highest maximum and RMS errors of 6.24 °C and 2.58 °C respectively. Both TM1 and TM2 could represent the measured TOT quite well under step loading. The simulated TOT for TM1 and TM2 are quite close to TE1 and close to measured TOT. The highest maximum and RMS errors for both TM1 and TM2 are 5.77 °C and 2.02 °C respectively.

It can be summarized that both TM1 and TM2 can be used as an alternative approach to determine the TOT with less input parameter and reasonable accuracy as compared to previous TOT thermal models.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMBANGUNAN TERMA MODEL SUHU MINYAK ATAS UNTUK ALAT-UBAH

Oleh

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Suhu Titik Panas (STP) didefinasikan sebagai suhu paling tinggi di dalam alat-ubah dan boleh ditentukan dengan menggunakan rangkaian terma model. Di dalam pendekatan ini, Suhu Minyak Atas (SMA) antara komponen penting untuk menentukan STP yang boleh dipercayai. Pada masa kini, terdapat dua panduan beban yang menggunakan terma model untuk menentukan SMA iaitu IEC 60076-7 and IEEE C57.91-1995. Terma model yang lain untuk SMA adalah berdasarkan kaedah terma-elektrikal analogi. Terdapat beberapa peningkatan yang boleh digunakan terhadap model SMA yang sedia ada seperti mengurangkan kesukaran terma model SMA dan meningkatkan ketepatan dimana adalah motivasi utama kajian ini. Tujuan utama kajian ini adalah untuk menyediakan pendekatan lain dalam menentukan SMA bagi alat-ubah. Dua terma model SMA telah dicadangkan dalam kajian ini dan dinamakan sebagai TM1 dan TM2. Terma model ini dibangunkan berlandaskan konsep laluan pemindahan tenaga. TM1 dibangunkan berdasarkan definisi baru rintangan terma melalui penghampiran pekali konveksi, *h*. Sementara itu, TM2 dibangunkan berlandaskan konsep ketidaklurusan rintangan terma yang mana masa pemalar minyak tertanam di dalam model dimana untuk meningkatkan ketepatan. Prestasi TM1 dan TM2 di nilai berdasarkan pengukuran SMA semasa ujian suhu naik dengan beban malar daripada 7 alat-ubah sama ada ONAN atau ONAF mod penyejukan. TM1 dan TM2 juga di uji dengan alat-ubah dengan beban dinamik. Prestasi TM1 dan TM2 di analisis melalui perbandingan dengan model terma-elektrikal terdahulu (dinamakan sebagai TE1 dan TE2), Exponen (IEC 60076-7) and Klaus 7 (IEEE C57.91-1995) terma model SMA. Di bawah beban malar, TM1 dan TM2 menunjukkan prestasi dengan baik berbanding model TE1 dan TE2. Prestasi TM1 dan TM2 juga adalah lebih baik daripada model Exponen dan Klaus 7 dalam mewakilkan pengukuran SMA. Untuk 7 alat-ubah, ralat maksimum dan Punca Min Kuasa Dua (PMKD) bagi TM1 ialah 6.66 ° C dan 2.76 ° C. Sebaliknya, TM2 mempunyai ralat maksimum dan PMKD pada 6.24 ° C dan 2.58 ° C. Kedua-dua TM1 dan TM2 boleh mewakili pengukuran SMA dengan baik di bawah beban dinamik. Simulasi SMA untuk TM1 dan TM2 agak dekat dengan TE1 dan hampir dengan pengukuran SMA. Ralat maksimum dan PMKD bagi TM1 dan TM2 masing-masing adalah 5.77 ° C dan 2.02 ° C. Ia dapat diringkaskan bahawa kedua-

dua TM1 dan TM2 boleh digunakan sebagai pendekatan alternatif untuk menentukan SMA dengan kurang masukan parameter dan ketepatan yang munasabah berbanding dengan terma model SMA sebelumnya.

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LIST OF ABBREVIATIONS

AC	Alternating current
AT	Ambient Temperature
BOT	Bottom Oil Temperature
DC	Direct current
FEM	Finite Element Method
HST	Hot-Spot Temperature
HV	High voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineer
LV	Low voltage
RC	Resistance capacitance
RMS	Root mean square
TE	Thermal-Electrical
TOT	Top-Oil Temperature
TM	Thermal model
TX	Transformer
ON	Oil Natural
OF	Oil Force
OD	Oil Directed
ONAN	Oil Natural-Air Natural
OFAF	Oil Force-Air Force
ONAF	Oil Natural-Air Force
ODAF	Oil Directed-Air Force
2D	Two dimensional

LIST OF SYMBOLS

A	Area
C	Constant
C_{indoor}	The indoor thermal capacitance
C_{oil}	The oil thermal capacitance
C_{th}	Thermal capacitance
C_{el}	Electrical capacitance
dt	The step time
$d\theta_{oil}$	The TOT that changes with step time
$d\theta_{ven-out}$	The ventilation temperature changes with step time
$d\theta_{hs}$	The HST changes with step time
f_1	The relative increase of the TOT rise
f_2	The relative increase of the HST rise
f_3	The relative decrease of the TOT rise
g_r	Oil gradient
h	Convection coefficient
H	Hotspot factor
I	Current
I_{rated}	Rated current
K	Load factor
K_U	The ratio of ultimate load to rated load
K_i	The ratio of initial load to rated load
k_{11}	Thermal model constant
k_{21}	Thermal model constant
k_{22}	Thermal model constant
m	The winding exponent
m_A	Weight of core and coil
m_{oil}	Transformer oil in liters
m_T	Weight of tank and fittings
n	The oil exponent/constant
P_{LL}	Load losses
P_{dc}	Losses due to dc winding resistance (IR losses)
P_{EL}	Winding eddy losses
P_{OSL}	Stray losses in others structural part
P_{SL}	Total stray losses
$P_{cu,pu}(\theta_{hs})$	The load losses dependence on temperature which can be seen in Equation (2.28)
$P_{cu,dc,pu}$	The dc losses in per unit value
$P_{cu,eddy,pu}$	The eddy losses in per unit value
$P_{l,pu}$	The load losses dependence on temperature that is calculated by Equation (2.30)
$P_{dc,pu}$	The dc losses in per unit value
$P_{a,pu}$	The additional losses (eddy and stray losses)
q	Heat source
q_1	The conduction through copper of the winding
q_2	The conduction through the insulation paper
q_3	The convection from insulation paper to the oil
q_4	The convection from the oil to the tank

q_5	The conduction through the tank/radiator of transformers
q_{fe}	The no load losses
q_{cu}	The load losses
q_{cabin}	The cabin losses
q_{in}	Input heat source
q_{oil}	Heat transfer rate of oil
q_{out}	Output heat source
R	Ratio of the load losses at rated current to no load losses
$R_{th,rated}$	Thermal resistance at rated
$R_{th,R}$	The oil thermal resistance at rated
$R_{tank/radiator}$	The thermal resistance of tank/radiator
t	Time
v	Voltage
x	Oil exponent
y	Winding exponent
θ	Temperature
θ_∞	The environment temperature
θ_h	The HST
θ_0	The TOT obtained from Equation (2.11)
$\theta_{ven-out}$	The ventilation temperature
θ_{oil}	The TOT
$\theta_{oil,measured}$	The measured TOT
$\theta_{oil,simulated}$	The simulated TOT
θ_a	The AT
θ_H	The HST
θ_A	The AT
θ_e	The temperature at which losses are estimated calculated by Equation (2.31)
θ_{hs}	The HST
$\theta_{e,rated}$	The rated mean HST
θ_k	The temperature factor for the loss correction
θ_s	The surface temperature
$\theta_{hs,lv}$	The high voltage winding HST
$\theta_{hs,hv}$	The high voltage winding HST
θ_{boil}	The BOT
$\theta_{ven-out}$	The ventilation temperature
$\Delta\theta_{oi}$	Initial TOT rise
$\Delta\theta_{or}$	TOT rise at rated load
$\Delta\theta_{hi}$	Initial HST rise
$\Delta\theta_h$	The HST rise obtained from Equation (2.11)
$\Delta\theta_{h1}$	HST rise calculated based on the Equation (2.14)
$\Delta\theta_{h2}$	HST rise calculated based on the Equation (2.15)
$\Delta\theta_{hr}$	The HST rise at rated load
$\Delta\theta_{oil}$	The TOT rise
$\Delta\theta_{TO}$	The TOT rise over AT calculated using Equation (2.18)
$\Delta\theta_H$	The winding HST rise over TOT calculated using Equation (2.19).
$\Delta\theta_{TO,U}$	The ultimate TOT rise over AT calculated using the Equation (2.20)

$\Delta\theta_{TO,i}$	The initial TOT rise over AT calculated using the Equation (2.21)
$\Delta\theta_{H,U}$	The ultimate winding HST rise over TOT calculated using the Equation (2.22)
$\Delta\theta_{H,i}$	The initial winding HST rise over TOT calculated using the Equation (2.23)
$\Delta\theta_{TO,R}$	The TOT rise over AT at rated load
$\Delta\theta_{H,R}$	The winding HST rise over TOT at rated load
$\Delta\theta_{BO}$	The BOT rise over AT
$\Delta\theta_{WO/BO}$	The temperature rise of oil at winding HST location over BOT
$\Delta\theta_{H/WO}$	The winding HST rise over oil next to HST location
$\Delta\theta_{oil,rated}$	The TOT rise at rated load
$\Delta\theta_{boil,rated}$	The BOT rise at rated load
$\Delta\theta_{hs-boil,rated}$	The HST to BOT rise at rated load
$\Delta\theta_{hs,rated}$	The HST rise at rated load
Δt	Time interval
τ_{oil}	The oil time constant
τ_{boil}	The BOT time constant
τ_{o}	The oil time constant
τ_{w}	The winding time constant
τ_{wdg}	The winding time constant
τ_{wdg-b}	The winding time constant
μ_{pu}	The oil viscosity in per unit value

CHAPTER 1

INTRODUCTION

1.1 Research Overview

Transformers are among the important equipment in the power system network. It usually consists of windings, cores, oils, papers, pressboard and a tank. The main function of transformers is to control the level of voltages of the networks [1]. It is critical to ensure transformers maintain operational at all times since its failure could be costly. Transformers asset management are normally carried out by utilities in order to ensure that the abnormal condition of transformers can be detected and mitigated as early as possible [2]. In addition, the scheme can ensure the reliability of the power system network can be maintain at acceptable level at all times [3, 4].

The components of transformers asset management include condition monitoring or assessment, maintenance plans or aging, health index and end-of-life evaluation [5]. Condition monitoring or assessment focuses on the application or development of the equipment or method that can be used to monitor the condition parameters in transformers. In recent years, a numbers of researches were carried out on the condition monitoring or assessment areas [6-10]. Among the common study is on the data analysis of condition parameters which can be used to evaluate the overall condition of transformers [5]. Among the condition parameters that can affect the lifetime of transformers is the Hot-Spot Temperature (HST) [11].

The components of the HST are Ambient Temperature (AT), Top-Oil Temperature (TOT) rise over AT, and HST rise over TOT [12]. Transformers with high HST can lead to advanced degradation of oils and winding. Under abnormal conditions, HST can lead to faults in transformers such as flashover between windings [13]. HST can be determined based on thermal study either through direct measurement or network thermal model [5]. Direct measurement can be carried out by means of fibre optic sensor. It is normally placed at a pre-determined location near to the topmost winding of transformers. It is the most accurate method to determine the HST; however, it is not widely available for application in all transformers due to the high cost and complexity of the fibre optic installation. Network thermal model can provide an approximation for the HST of transformers which can be carried out by either using the Finite Element Method (FEM) or numerical equation. Thermal modelling based on FEM can be carried out through physical modelling using software such as ANSYS and COMSOL [14]. On the other hand, thermal modelling based on numerical equation can be carried out based on the temperature rise report and design information of transformers. Currently, there are 2 loading guides that utilize the numerical equations to model the TOT and HST of transformers which are the IEC 60076-7 and IEEE C57.91-1995 [12, 15]. IEC 60076-7 has 2 numerical equation thermal models that consist of the Exponential and Differential models. Both models are capable to determine the TOT and HST under steady state and dynamic conditions respectively. There are also 2 numerical equation thermal models for IEEE C57.91-1995 known as the Clause 7 and Annex G models.

Apart from the loading guides models, a numbers of studies were also carried out on the development of alternative HST and TOT thermal models based on thermal-electrical analogy method [16-20]. Swift model proposed the concept of heat transfer equivalent circuit analogy to RC circuit based on thermal-electrical analogy method [16, 21]. Dejan Susa model extended the application of thermal-electrical analogy method through inclusion of nonlinear thermal resistance which was defined by using the Nusselt, Prandtle and Grashof numbers [17]. Other study used the same concept of thermal-electrical method to obtain the input parameters such as the TOT rise at rated, oil time constant and constant *n* based on Levenberg-Marquardt method utilizing the in-service measured data [18]. The thermal-electrical analogy method was also applied to obtain the outdoor and indoor TOT thermal models [19, 20] The thermal-electrical circuit for outdoor was the same as in [16-18] while the thermal-electrical circuit for indoor cases required a considerable amount of thermal resistances information such as windings, oil, core, tank, cooling air, ventilation holes, walls and ceiling. The heat generated in distribution cabinet is also taken into account in the indoors of the thermal-electrical circuit. In this study, alternative approaches to determine TOT are proposed based on thermal-electrical analogy method where a new concept of heat pathway of energy is proposed.

1.2 Problem Statement

TOT is one of crucial components of the HST in the numerical equations thermal models. The accuracy of the HST depends on the TOT; hence, making it important to develop a reliable TOT thermal models. Currently, there are 2 loading guides that use the numerical equations thermal models to determine the TOT known as IEC 60076-7 and IEEEC57.91-1995 loading guides. However, there are several issues for the existing network thermal model provided by these loading guides which are stated as follows.

1. The rise and fall curves of the TOT for Exponential model in IEC 60076-7 are difficult to be controlled and are not suitable for dynamic loading. In addition, both Exponential and Differential models have multiple constants which may not suitable for different types of transformers designs. For Differential model, the initial TOT is obtained based on equation where a number of assumptions are made which might lead to inaccuracy to the final TOT.
2. Clause 7 model in IEEE C57.91-1995 is quite simple which leads to inaccuracy in modelling the TOT. On the other hand, Annex G model is quite complicated and requires parameters that may not be readily available for most of transformers.

Apart from the IEC 60076-7 and IEEE C57.91-1995, there are other approaches that can be used to determine the TOT of transformers based on the thermal-electrical analogy method and among the common models are the Swift and Dejan Susa approaches. These models are in the form of differential equation and can provide TOT that are closer to measured TOT. However, there are few issues with these models which are listed are as follows.

1. The concept of heat transfer theory to derive the thermal-electrical analogy circuit is not well defined in the Swift model. Furthermore, the input data such as TOT rise at rated load, oil time constant and constant *n* are determined based on parameter estimation method. This method required in-service measured TOT in order to estimate the input parameters which may not be available for all transformers.
2. Dejan Susa model requires the oil viscosity and variation of load loss information which increases the complexity of the equation.

Considering these issues, a study is needed in order to develop alternative thermal models which require less input parameters as well as that can generate results that are close to the measured values.

1.3 Research aim and objectives

The aim of this research is to develop an alternatives TOT thermal models for transformers. The objectives are as follows.

1. To develop the thermal-electrical analogy circuit based on the concept of the pathway of energy.
2. To propose alternative numerical equation for TOT thermal model based on the approximation of convection coefficient, *h* (Thermal Model 1 – TM1) which does not require the information on the viscosity.
3. To propose alternative numerical equation for TOT thermal model based on the concept of nonlinearity of thermal resistance (Thermal Model 2 – TM2) which reduce the complexity of the previous TOT equation.

1.4 Scope of work

The scope and limitations of this research work are as follows:

1. This research focuses only on the determination of TOT thermal model based on numerical equations.
2. The data used in this research and simulation is obtained from heat run test reports of distribution transformers with voltage level of 33 kV and power ratings between 300 kVA and 90 MVA and IEC 60076-7 report of a transformer with voltage level 250 kV and power rating of 250 MVA. The heat run test is the type test carried out to verify the guaranteed temperature rises and consists of 3 consecutive steps. The first step is transformer subjected to the sum of the load and no-load losses until TOT is established. The second step is continue with test current reduced to rated current for 1 hour. The last step is the shutdown stage.

1.5 Thesis outline

This thesis consists of five chapters: introduction; literature review; methodology; results and discussion; and conclusions and recommendations for future work.

Chapter 1 Introduction
This chapter presents the research overview, problem statement, research aim and objectives and also the scope of work of the study.

Chapter 2 Literature Review
This chapter provides a literature review of related fields to this study which includes an overview of transformer structures, transformer stresses, heat source, transformer cooling system and thermal profile. Also, the methods to determine transformer HST and TOT were also reviewed and discussed in this chapter.

Chapter 3 Methodology
This chapter presents the development of TOT thermal models. It is developed based on fundamentals of heat transfer theory and thermal-electrical analogy. There are 2 TOT thermal models namely as TM1 and TM2 that have been developed and presented in this chapter.

Chapter 4 Results and Discussion
This chapter discusses the performance of TM1 and TM2 which were developed in Chapter 3. The TM1 and TM2 were evaluated based on measured TOT during temperature rise test for 7 transformers. In addition, the TM1 and TM2 were also tested on the step loading of a 250 MVA transformer with ONAF cooling mode. The performance of these models were analysed through comparison with existing Thermal-Electrical, Exponential (IEC 60076-7) and Clause 7 (IEEE C57.91-1995) models.

Chapter 5 Conclusion and Recommendations
This chapter summarizes and concludes the findings of this research. The contributions of the study also included in this chapter. Recommendation of future study on network thermal model by numerical equation can also be discovered at the end of this chapter.

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