OPTIMIZING THE EFFECTIVENESS OF FAN GROUP SETTINGS FOR LIFE EXTENSION AND LOAD INCREMENT OF AGEING TRANSFORMERS

Don Tharindu Prathap Wijesuriya

208770B

Master of Science in Electrical Engineering

Department of Electrical Engineering
Faculty of Engineering

University of Moratuwa
Sri Lanka

April 2023

OPTIMIZING THE EFFECTIVENESS OF FAN GROUP SETTINGS FOR LIFE EXTENSION AND LOAD INCREMENT OF AGEING TRANSFORMERS

Don Tharindu Prathap Wijesuriya

208770B

Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree
Master of Science in Electrical Engineering

Department of Electrical Engineering
Faculty of Engineering

University of Moratuwa
Sri Lanka

April 2023

DECLARATION

I declare that this is my own work and this thesis/dissertation does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other University or Institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: Date: 24/04/2024

The above candidate has carried out research for the PhD/MPhil/Masters thesis/dissertation under my supervision. I confirm that the declaration made above by the student is true and correct.

Name of Supervisor:

1. Dr. Rasara Samarasinghe
2. Dr. K.M Kapila Bandara

Signature of the Supervisor: Date:

1. ……………………………….. 22/05/2024 …………………
2. ……………………………….. 22/05/2024 …………………

ACKNOWLEDGEMENT

I wish to convey my sincere gratitude to the individuals who have been pivotal in the successful completion of this thesis.

First and foremost, I extend my heartfelt appreciation to Dr. Rasara Samarasinghe and Dr. K.M. Kapila Bandara for their exceptional supervision and invaluable guidance, without which this research would not have been possible.

I am deeply indebted to the lecturers of the Electrical Engineering Department at the University of Moratuwa, who not only provided me with the theoretical foundation but also offered unwavering support throughout the study, transforming theory into practical and meaningful contributions.

I must also express my profound thanks to my colleagues at the Ceylon Electricity Board. Their generosity in sharing their knowledge and their guidance during moments of uncertainty have played a crucial role in the successful completion of this study.

To my fellow postgraduate program colleagues, your encouragement and support have been a constant source of inspiration.

Lastly, but by no means least, I reserve my dearest thanks and a profound sense of gratefulness for my family members - my father, mother, wife, and sister. Their compassionate words and unwavering guidance have not only shaped this thesis but also my vision to make a meaningful contribution to society and the world.

This work stands as a testament to the collective support and encouragement of these wonderful individuals, and I am truly thankful for their presence on this journey.

ABSTRACT

This thesis aims to address the critical challenge of optimizing the operational lifespan of aging transformers within the Sri Lankan Power System. Through a multidisciplinary approach, incorporating mathematical modeling, environmental analysis, and cost optimization techniques, a comprehensive framework for transformer management is developed.

The primary objective of this research is to extend the operational life of aging transformers while maximizing loading, and cost efficiency by adjusting cooling fan group settings. To achieve this goal, the study begins by investigating the aging process of transformers and identifying key factors influencing their lifespan. Calculations are done to quantify the effects of temperature, moisture, and oxygen exposure on transformer insulation aging. These findings are integrated into mathematical models, which accurately predict transformer lifetimes based on environmental conditions and operational parameters.

Moreover, a cost optimization model is developed to assess the financial implications of different combinations of fan settings and loadings, encompassing maintenance costs, energy consumption, and potential savings. By considering these factors holistically, utility companies can make well-informed decisions regarding transformer management and retirement, ultimately leading to substantial cost savings and improved operational efficiency.

The results of the study demonstrate the effectiveness of the cooling fan group settings in extending transformer lifespans, increasing the loading and optimizing costs. Sensitivity analysis is performed to understand the varying impact of input parameters on model outcomes, providing valuable insights for future research and optimization efforts.

In conclusion, this thesis contributes significantly to the field of power system management by providing a practical and data-driven approach to transformer management. The developed framework ensures the reliability and sustainability of power systems in Sri Lanka and beyond, thus laying the groundwork for enhanced operational efficiency and cost-effectiveness in the management of aging transformer.

Keywords: ageing transformers, hotspot temperature, paper insulation, Degree of Polymerization, fan group settings, mathematical modelling.

TABLE OF CONTENTS

Declaration i

Acknowledgement ii

Abstract iii

Table of Contents iv

List of Figures ix

List of Tables xi

List of Abbreviations xiii

List of Appendices xiv

Chapter 1 Introduction 1

1.1 Background 1

1.2 Problem Statement and Aim of the Study 1

1.2.1 Problem Statement 1

1.2.2 Aim of the Study 3

1.3 Objectives and Scope of Work 4

1.3.1 Main Objective 4

1.3.2 Specific Objective 4

1.3.3 Scope of Work 4

Chapter 2 Literature Review 6

2.1 Power Transformers 6

2.2 Transformer Insulation 6

2.2.1 Insulation Oil 6

2.2.2 Paper Insulation 7

2.2.3 Pressboard 8

2.2.4 Wood 9

2.3 Ageing of Transformer Insulation 9

2.3.1 Residual Moisture in Thick Structure Elements on Oil 11

2.3.2 Water from Cellulose paper 11

2.3.2 Moisture Ingress 12

2.4 Mechanism of controlling the ageing agents in Transformer 13

2.4.1 Silica Gel Breather ... 13
2.4.2 Breathing types ... 14
2.5 Ageing Studies of Transformers ... 15
2.5.1 Relationship between Degree of Polymerization and the Ageing ... 15
2.5.2 Effect of Moisture on Ageing ... 15
2.5.3 Effect of Oxygen on Ageing ... 16
2.6 Effect of Hotspot Temperature on Transformer Ageing ... 17
2.6.1 Calculation of Hotspot Temperature ... 17
2.6.2 Top oil temperature raise over ambient temperature ... 18
2.6.3 Ultimate and initial top oil temperature raises over ambient temperature 18
2.6.4 Oil time constant ... 19
2.6.5 Winding Hotspot raise ... 20
2.6.6 Ultimate and initial winding hotspot temperature raise over top oil temperature ... 21
2.6.7 Exponents used for temperature determination equation ... 21
2.7 Transformer Cooling fans ... 22
Chapter 3 Methodology ... 23
3.1 Introduction ... 23
3.2 Calculation of Moisture Content ... 25
3.2.1 Moisture adding through inhaling ... 25
3.2.2 Moisture adding through oil leaks ... 28
3.2.3 Moisture adding through paper ageing ... 28
3.2.4 Moisture removing by oil filtering ... 28
3.2.5 Monthly moisture content calculation ... 29
3.3 Estimation of Oxygen Level ... 31
3.4 Calculation of ‘A’ ... 32
3.4.1 Calculation of MFm ... 32
3.4.2 Calculation of MFom ... 33
3.4.3 Calculation of MFoh ... 33
3.4.4 Monthly Calculation of ‘A’ ... 34
3.5 Calculation of ‘k’ ... 34

3.6 Calculation of 'DP' and ageing estimation 34
3.7 Remaining lifetime estimation 35
3.8 Development of the Mathematical Model 36
3.8.1 Overview of the Mathematical Model 36
3.8.2 Thermal Model 37
..... 38
3.8.3 Transformer Remaining Life Estimation Model 41
3.8.4 Cost Optimization Model 42
Chapter 4 Lifetime Estimation Of Ageing Power Transformers 46
4.1 Transformer Details under the Scope 46
4.2 Calculation of Moisture Content 46
4.3 Estimation of Moisture Absorption of Silica Gel in Breathers 47
4.3.1 Moisture absorption experiment at 75% Relative Humidity 48
4.3.2 Experiment on Actual moisture absorbed by Breather in Madampe Transformer 02 51
4.4 Calculation of Moisture Adding through Inhaling 54
4.4.1 Amount of moisture ingress to the Transformer 54
4.4.2 Amount of moisture remained in the Transformer 58
4.5 Moisture Absorbed through Oil Leakages 60
4.6 Moisture Adding through Ageing of Paper 61
4.7 Moisture removed through oil filtering 69
4.7.1 Offline oil filtering 69
4.7.2 Online oil filtering 71
4.8 Dynamic Calculation of Moisture Content % 72
4.9 Assessment of Oxygen content of Transformers 74
4.9.1 Oxygen content measurement 74
4.10 Calculation of Pre exponential factor (A) 76
4.10.1 Calculation of multiplication factors for pre exponential factor A 76
4.10.2 Multiplication Factors of A for Moisture at Low Oxygen level (O2< 7000ppm) 76
4.10.3 Multiplication Factors of A for Moisture at medium oxygen level (7000ppm < O2< 14000ppm) (MFom) 78

4.10.4 Multiplication Factors of A for Moisture at high oxygen level (14000ppm < O2) (MFoh) 80
4.11 Calculation of Ageing rate (k) 83
4.11.1 Identification of Hot Spot Temperatures of Transformers 84
4.11.2 Temperature data collection 84
4.11.3 Calculation of k 86
4.12 Calculation of Degree of Polymerization (DP) 87
4.12.1 Estimation of Ageing as at Now 88
4.12.2 Estimation of remaining lifetime 90
4.13 Results verification through DIRANA and correction 93
4.13.1 Estimation of Moisture % using DIRANA test 93
4.13.2 Calculation of error in estimated life 95
4.13.3 Corrected remaining lifetime of Transformers 96
Chapter 5 Thermal Model For Of Ageing Power Transformers 97
5.1 Transformer Data Required for Thermal Model 97
5.1.1 Weight data of transformers 97
5.1.2 Cooling methods and cooling fan temperature settings 98
5.1.3 Factory Test Data of Transformers 99
5.1.4 Calculation of data for Fan Group 1 100
5.2 Calculation of parameters related to hotspot temperature 102
5.2.1 Calculation of Ratio of load loss at rated load to no load loss (R)..... 102
5.2.2 Calculation of Thermal Capacity of Transformers 103
5.2.3 Calculation of time constant for rated load (ƮTO,R) 104
5.3 Hot spot temperature calculation for thermal model 104
5.3.1 Estimation of existing load curve 104
5.3.2 Hotspot Temperature Calculation Algorithm 105
Chapter 6 Transformer Remaining Life Estimation Model 106
6.1 Introduction 106
6.2 Function of the Model 106
Chapter 7 Cost Optimation Model 107
7.1 Introduction 107
7.2 Costs of Implementation of the Model 107

7.2.1 Load Losses 107
7.2.2 Auxiliary Losses 108
7.3 Benefit of Implementation of the Model 109
7.3.1 Transformer Cost Calculation 109
7.3.2 Deferred replacement cost 110
7.3.3 Saving due to increased loads 111
7.4 Net Benefit Calculation 112
Chapter 8 Results And Accuracy Of The Model 113
8.1 Results 113
8.2 Accuracy of the Model 117
8.2.1 Model Prediction Accuracy 117
8.2.2 Model Parameter Sensitivity 118
Chapter 9 Conclusion 120
9.1 Summary and Conclusion 120
9.2 Suggestion for Future Projects 121
References 123

LIST OF FIGURES

Figure Description	Page
Figure 2.1 Molecular structure of the cellulose	7
Figure 2.2 Paper insulation of Transformer	8
Figure 2.3 Pressboard	8
Figure 2.4 Oxidation process	9
Figure 2.5 Pyrolysis degrading process	10
Figure 2.6 Hydrolysis process	10
Figure 2.7 Relation between Water content and Chain scissions	11
Figure 2.8 Conventional Breather	13
Figure 2.9 Maintenance free breather	14
Figure 2.10 Diaphragm and Air Cell arrangement in Conservator tank	14
Figure 3.1 Whole calculation in graphical view	24
Figure 3.2 Relation among temperature, RH and water content in air	26
Figure 3.3 Moisture content calculation in flow chart	30
Figure 3.4 DP calculation in flow chart	35
Figure 3.5 Mathematical Model Overview	37
Figure 3.6 Thermal Model	38
Figure 3.7 Transformer Remaining Life Estimation Model	42
Figure 3.8 Cost Optimization Model	43
Figure 4.1 Moisture absorption characteristics by Silica gel in general	47
Figure 4.2 Experiment arrangement at 75% relative humidity	50
Figure 4.3 Moisture absorption at 75% relative humidity	50
Figure 4.4 Breather at Madampe Transformer 02	52
Figure 4.5 Experiment on breather at Madampe Transformer 02	52
Figure 4.6 24 hour oil temperatures in January for Madampe TF02	55
Figure 4.7 24 Hour average oil temperatures in January for Madampe TF02	55
Figure 4.8 Calculated remained moisture amount through inhaling in Madampe Transformer 02 for 2015	60
Figure 4.9 Relation between moisture content and chain scission	62
Figure 4.10 Relation between moisture content and chain scission up to 2	62

Figure 4.11 Relation between moisture content and DP 63
Figure 4.12 Moisture variation of Madampe Transformers with DP 64
Figure 4.13 Relation between moisture content and DP 65
Figure 4.14 Relation between water and chain scission 66
Figure 4.15 Relation between Summarized moisture content and DP 68
Figure 4.16 Relation between Moisture content and DP of Madampe Transformer 02 68
Figure 4.17 DGA report of Madampe Transformer 01 75
Figure 4.18 Multiplication factor variation at low O_2 level 78
Figure 4.19 Multiplication factor variation at medium O_2 level 80
Figure 4.20 Multiplication Factor variation at high O_2 level 82
Figure 4.21 24 Hour winding temperatures of Madampe TF02 for January 85
Figure 4.22 24 Hour average winding temperature of Madampe TF02 for January 85
Figure 4.23 Variation of moisture content of Madampe TF02 till 2023 89
Figure 4.24 Variation of moisture content of Puttalam TF01 till 2023 89
Figure 4.25 Variation of DP of Madampe TF02 till 2023 90
Figure 4.26 Variation of DP of Puttalam TF01 till 2023 90
Figure 4.27 Variation of moisture content of Madampe TF02 till end of life 91
Figure 4.28 Variation of moisture content of Puttalam TF01 till end of life 91
Figure 4.29 Variation of DP of Madampe TF02 till end of life 92
Figure 4.30 Variation of DP of Puttalam TF01 till end of life 92
Figure 4.31 Descriptive DIRANA curve 94
Figure 4.32 DIRANA test result of MadampeTF02 94
Figure 5.1 Average daily load pattern of Madampe Transformer 105

LIST OF TABLES

Table	Description	Page
Table 2-1	Water contamination due to different mechanism	12
Table 2-2	Summary of values of ‘A’ from different researches	16
Table 2-3	‘A’ values at different moisture contents	16
Table 2-4	Exponents ‘n’ and ‘m’ values	21
Table 3-1	Definition of Oxygen levels	31
Table 3-2	Multiplication factor calculations	32
Table 4-1	Details of Transformers	46
Table 4-2	Maximum estimated moisture absorption by breather for Transformers	51
Table 4-3	Calculated added moisture in Madampe TF 2 for 2015	59
Table 4-4	Oil leakages details	60
Table 4-5	Equalized Moisture content values for 1000 DP	66
Table 4-6	Moisture at different DP values	67
Table 4-7	Oil filtering data of Transformers	71
Table 4-8	Calculated moisture content of Madampe Transformer 02 for 2010	73
Table 4-9	DGA test results	75
Table 4-10	Multiplication factors for different moisture contents at low O_2 level	77
Table 4-11	Multiplication factors for different moisture contents at medium O_2 level	79
Table 4-12	Multiplication factors for different moisture contents at high O_2 level	81
Table 4-13	Calculated present DP, Moisture content and remaining life of TFs	93
Table 4-14	Calculated and estimated moisture content data	95
Table 4-15	Calculation errors of Transformers	96
Table 4-16	Corrected remaining life of Transformers	96
Table 5-1	Weight details of Transformers	97
Table 5-2	Calculated weight and oil capacity details of Transformers	98
Table 5-3	Fan Group operation settings of Transformers	99
Table 5-4	FAT data of similar Transformers	100
Table 5-5	Calculated Rated data for Fan Group 1 and 2	102
Table 5-6	Calculated ‘R’ values	102

Table 5-7 Calculated ‘C’ values for studied Transformers 103
Table 5-8 Calculated Time constant 104
Table 7-1 Cost Figures of Transformers 110
Table 8-1 Top 10 optimized solutions for Madampe Transformer 2 113
Table 8-2 Top 10 optimized solutions for Puttalam Transformer 1 114
Table 8-3 Top 10 optimized solutions for Puttalam Transformer 2 115
Table 8-4 Summary of predicted transformer life with new settings 116
Table 8-5 Model Prediction Accuracy 117
Table 8-6 Sensitivity Analysis - Ambient Temperature 118
Table 8-7 Sensitivity Analysis – Moisture in Air 119
Table 8-8 Sensitivity Analysis - Loading 119

LIST OF ABBREVIATIONS

Abbreviation	Description
OH	Hydroxyl
RH	Relative Humidity
DP	Degree of Polymerization
O2	Oxygen
GS	Grid Substation
TF	Transformer
DGA	Dissolve Gas Analysis
PPM	Parts Per Million
HRS	Hours
NaCl	Sodium Chloride
MFm	Multiplication factor of 'A' for moisture
MFom	Multiplication factor of 'A' for moisture at medium Oxygen level
MFoh	Multiplication factor of 'A' for moisture at high Oxygen level
FAT	Factory Acceptance Tests
DIRANA	Dielectric Frequency Response Analysis
AC	Alternating Current
ONAN	Oil Natural Air Natural
ONAF	Oil Forced Air Forced

LIST OF APPENDICES

Appendix **Description** **Page**

Appendix A - Average oil temperatures of the three TFs for 12 months 126
Appendix B - Special Maintenance report of oil filtering of Bolawatta TF 127
Appendix C - Average LV winding temperatures of 6 TFs for 12 months 130
Appendix D - Hourly ageing calculation and moisture calculation of Madampe TF 02 (1994) 131
Appendix E - Moisture content variations till 2023.. 139
Appendix F - DP variations till 2023 140
Appendix G - Moisture content variations till end of lifetime................................ 141
Appendix H - DP variations till end of lifetime 142
Appendix I - DIRANA measurements of all TFs 143
Appendix J - FAT report of Chunnakkam TF... 144
Appendix K FAT report of Kegalle TF... 147
Appendix L - FAT report of Kotugoda TF 149
Appendix M - FAT report of Maho TF... 152
Appendix N - FAT report of Kiribathkumbura TF 156
Appendix O - Average 24 hour Load curves of Madampe & Puttalam TFs 158
Appendix P – Thermal Model Code 159
Appendix Q – Thermal Model Results – Madampe TF 2.. 167
Appendix R – Transformer Life Estimation Model Code 172
Appendix S - Transformer Life Estimation Model – Results – Madampe TF 2...... 178
Appendix T – Cost Optimization Model Code 186
Appendix U - Cost Optimization Model Results 193

CHAPTER 1 INTRODUCTION

1.1 Background

Power Transformers are vital equipment in transmission networks used to step down the Transmission voltages (220 kV, 132 kV) to distribution level (33 kV, 11 kV) and further 220 kV voltage is reduced to 132 kV in Switching Stations in Sri Lankan power system. Nearly almost all the power Transformers in the world are oil immersed type Transformers mainly due to facts that availability, low cost and better chemical stability of mineral oil. These oil immersed type power transformers have a lifespan of around 30 – 40 years. Sri Lankan power network consist of 221 power transformers, and 25% out of them are over 25 years of old.

Insulation system of oil filled Transformer mainly consists of cellulose-based paper or press board solid insulation and mineral oil. Paper insulation is the most important part of the Transformer insulation system which decides the life time of Transformer. This is because, paper insulation cannot be replaced due to a failure, damage or ageing. Paper insulation used in Transformer is a polymer of cellulose which has degree of polymerization (DP) of about thousand at the beginning [1]. New paper insulation with about thousand DP has enough dielectric and mechanical strength to withstand during intense situation like short circuit. However, paper insulation in Transformer age due to combined effect of moisture, temperature and Oxygen which are readily available in operational Transformers. Ageing causes to decrease cellulose polymer length and mechanical strength of cellulose insulation. It is generally accepted that, paper insulation cannot withstand during a short circuit fault when the DP reach to about 200 and therefore, value of DP of 200 is considered as the end of life of the paper insulation. [1]. Temperature is one of the main operational parameters which decides the lifetime of paper insulation and hence Transformer. Hot spot temperature decreases or increases with the load reduction or increment. It is widely accepted that the insulation degradation approximately doubles with every 6 °C increase of temperature. This relationship implies that even a relatively small increase in operating temperature can lead to a substantial increase in insulation degradation. Therefore, precise control of temperature, which can be influenced by factors such as fan group settings, is of paramount importance to mitigate insulation degradation and extend the operational life of aging transformers.

1.2 Problem Statement and Aim of the Study

1.2.1 Problem Statement

Aging powers transformers within electrical power systems pose a significant challenge to the utility industry. These transformers, over time, experience natural wear and tear, leading to increased vulnerability to failures. Managing the health and longevity of aging transformers is a multifaceted problem that requires addressing the issue of rising temperatures under load increment conditions.

Utilizing cooling fans in a transformer are commonplace, but the optimal configuration of fan group settings to effectively mitigate temperature rise and extend the lifespan of aging transformers remains a critical concern. The problem lies in the lack of a systematic and data-driven approach for optimizing fan group settings under various load profiles, leading to suboptimal cooling efficiency, increased energy consumption, and elevated operational costs.

The Sri Lankan (SL) Power System is facing a multifaceted challenge concerning its aging transformer infrastructure:

1. Reaching Theoretical Design Life: A substantial portion of transformers within the Sri Lankan Power System is approaching or has reached their theoretical design life. The aging of transformers is a natural process that introduces vulnerabilities, increasing the risk of operational failures and costly replacements. Despite this, there is currently no comprehensive aging estimation method that incorporates all critical parameters necessary to assess the condition of transformers accurately.

Several laboratory investigations have been conducted to understand the effect of temperature, moisture and Oxygen on ageing of transformer paper insulation. Further, effects of those factors on ageing of paper insulation have been quantified by providing mathematical relationships. However, application of finding of laboratory studies of field Transformers can be rarely found mainly due to fact that difficulty in finding of accurate operational data and the complexity of the data. Ageing of Transformer is almost referring to the ageing condition of paper insulation of transformer. This is because ageing of paper is an irreversible process and it cannot be replaced. Further, according to the Transformer reliability survey report of CIGRE working group A2.37 nearly 40% of Transformer failures around the world are due to winding paper insulation issues [2]. And moreover, as per the survey of Australian power Transformer failures and retirement, nearly 50% of Transformer failures are due to winding insulation failures.

Hence, one of the aims of this research is to perform an ageing study of paper insulation of selected Transformers from CEB Transmission Network considering the other operational parameters such as dynamic moisture and oxygen variation which have not been accounted in controlled laboratory insulation ageing experiments. Further, outcome of this research can be used to have a generalized idea of ageing condition of Transformers in CEB Transmission network.

2. Underutilization of Aging Transformers: Aging transformers in Sri Lankan Power System are often underloaded, not utilized to their full capacity, as a precautionary measure to prevent breakdowns and accelerated aging. However, this conservative approach results in underutilized assets, leading to operational inefficiencies and increased maintenance costs.

3. Rising Electricity Demand: The demand for electricity in Sri Lanka is steadily increasing. In order to meet this increasing demand either it is required to increase the loading of the existing transformers or additional transformers need to be purchased, which come at a substantial financial cost. The procurement of new transformers, while necessary, presents a financial burden to utility companies.

Therefore, the collective issue at hand is the need to develop a methodology that addresses these challenges by optimizing the loading of aging transformers, effectively extending their operational life in a cost-efficient manner. This methodology should consider the triad of challenges - aging, underutilization, and the increasing demand for electricity.

1.2.2 Aim of the Study

The primary aim of this study is to develop a comprehensive life extension and load increment technique through the temperature adjustment of fan group settings in aging transformers within the Sri Lankan Power System. This technique will be designed in such a way that it optimizes costs over the remaining operational life of an aging transformer. Specifically, the study aims to:

1. Optimize Fan Group Temperature Settings: Develop and implement a data-driven approach to optimize fan group settings that effectively manage temperature and insulation degradation, thereby extending the operational life of aging transformers.

2. Integrate Load Increment Strategies: Design strategies that allow for the increased loading of aging transformers while ensuring that the rate of aging remains within acceptable limits, preventing unexpected failures and maintaining cost efficiency.

3. Cost Optimization: Develop a cost-efficient methodology that considers the trade-offs between maintenance costs, energy consumption, and transformer replacement costs over the remaining lifespan of aging transformers.

The outcome of this research will provide a practical framework for any utility company to maximize the utility of aging power transformers, reduce the financial burden of new transformer procurement, and ensure the long-term reliability and sustainability of their power system. The ultimate aim is to strike a balance between operational efficiency and cost optimization throughout the remaining life of aging transformers.

1.3 Objectives and Scope of Work

1.3.1 Main Objective

The main objective of this study is to develop a comprehensive mathematical model that focuses on life extension and load increment for aging transformers by finding the most effective cooling fan group temperature settings in such a way that the overall cost is optimized over the remaining operational life of an aging transformer.

1.3.2 Specific Objective

In pursuit of the main objective, the following specific objectives will be addressed:

1. **To Estimate the Remaining (Useful) Lifetime of a Transformer:** Develop a reliable estimation methodology for assessing the remaining operational lifetime of aging transformers. This estimation will be based on the degree of polymerization of paper insulation, a key indicator of transformer health.
2. **To Assess Environmental Factors that Affect the Useful Life of a Transformer:** Investigate and quantify the impact of environmental factors such as moisture, oxygen exposure, and hot spot temperature on the remaining lifetime of transformers. These are the major factors that influence the rate of aging in transformers.
3. **To Determine Optimum Fan Group Settings:** Utilize aging parameters and financial analysis to determine the most effective cooling fan group settings. These settings will be optimized to mitigate temperature rise, extend the transformer's operational life, and minimize energy consumption.
4. **To Develop Maintenance Strategies:** Formulate a comprehensive maintenance strategy that is specifically tailored to aging transformers. This strategy will focus on proactive measures to extend the remaining operational life of aging transformers, balancing the cost of maintenance with the benefits of prolonged service life.

By achieving these specific objectives, this study aims to provide utility companies and industrial sectors with a scientifically grounded, cost-effective methodology for managing aging transformers while ensuring their reliability and sustainability throughout the remaining operational lifespan.

1.3.3 Scope of Work

This research aims to investigate the aging process of transformers within the Sri Lankan Power System and develop an optimized cooling fan strategy to extend their operational lifespan optimization. Three transformers were selected for the study from Madampe and Puttalam Grid Substations. The primary objectives include analyzing factors contributing to transformer aging, developing a mathematical model to estimate remaining operational life, designing a data-driven approach to optimize cooling fan settings, and assessing the economic feasibility of the proposed strategy. The study will adopt a mixed-methods approach, combining quantitative analysis, mathematical modeling, and data-driven optimization techniques. Data will be collected from aging transformers nearing the end of their theoretical design life, focusing on temperature measurements, load profiles, and maintenance records for aging calculations. A mathematical model was developed to find the optimized cooling fan strategy in the way that transformer life is improved while increasing the loading. Further, the outcomes were validated and model accuracy was checked using the sensitivity analysis. The study will be conducted within the geographical boundaries of the Sri Lankan Power System. Limitations may include data availability and quality, resource constraints, etc. The expected outcomes include insights into transformer aging mechanisms, practical recommendations for cooling fan optimization along with improving the loadings while extending the transformer lifetime, and implications for transformer maintenance practices and cost savings within the Sri Lankan Power System. This research aims to contribute to the body of knowledge on transformer aging and cooling fan optimization, informing industry best practices, policy decisions, and future research directions in electrical engineering and power systems management.

CHAPTER 2 LITERATURE REVIEW

2.1 Power Transformers

Power transformers are critical components in electrical power systems, playing a central role in voltage regulation and efficient energy transmission. These devices facilitate the step-up or step-down of voltage levels, ensuring electricity can be transmitted over long distances with minimal losses. Grid Transformers are always used to reduce Transmission voltages (220 kV, 132 kV) to distribution voltages (33 kV). Based on the insulation system of Transformers, they can be categorized in to dry, oil filled and gas filled Transformers. Almost all the power Transformers in the world are oil filled Transformers with cellulose insulation. As moisture and Oxygen are detrimental to the Transformer solid insulation, necessary arrangement has to be made to avoid direct contact with environmental air. Thus, oil filled Transformer can be a hermetically sealed or air breathing type.

2.2 Transformer Insulation

Transformer insulation system mainly comprises of following items.

1. Insulation oil
2. Paper insulation
3. Pressboard
4. Wood

2.2.1 Insulation Oil

The use of insulation oil in power transformers is a fundamental and indispensable aspect of electrical engineering. This essential component provides a range of key properties that make it well-suited for its role in these critical systems. Mineral oil-based insulation oils, commonly employed in the power industry, possess three pivotal properties that make them the ideal choice for transformers, and these properties remain remarkably stable even when subjected to elevated temperatures for extended durations.

Firstly, insulation oil boasts an exceptional high thermal conductivity. This inherent quality enables it to efficiently absorb and transfer the heat generated within the transformer windings to the cooling surfaces. As a result, insulation oil serves a dual purpose: it not only insulates the components but also functions as a cooling medium, effectively curbing temperature increases within the transformer.

Secondly, insulation oil exhibits a remarkable high dielectric strength. The dielectric strength of the oil represents its ability to withstand high voltages without suffering breakdown. According to the IEC 60156:2018 standard, a minimum dielectric strength of 30 kV/2.5mm at 27°C is required for its use in transformers. It's important to note that while insulation oil may have robust dielectric properties under standard conditions, aging and moisture ingress can significantly diminish this critical attribute over time.

Lastly, high chemical stability characterizes insulation oil. It demonstrates an ability to withstand chemical decomposition even when exposed to elevated temperatures to a certain extent. This chemical stability ensures that the oil maintains its integrity and functionality, providing long-term insulation and cooling properties within the transformer.

2.2.2 Paper Insulation

Cellulose paper insulation is a cost-effective and sustainable choice for transformers, providing vital insulation between live components and the earth. Common types include Kraft paper and press boards. Cellulose paper insulation is manufactured using coniferous trees. While cellulose paper naturally contains organic contaminants like hemicellulose and lignin, which effect badly on the insulation property of paper, these are removed during manufacturing by boiling the wood in an alkaline solution. The resulting composition consists of about 90% cellulose, 6-7% hemicelluloses, 3-4% lignin, and less than 0.5% inorganic salts, ensuring optimal insulation properties [3]. This balance between cost-effectiveness and performance is essential for transformer reliability and longevity. Paper has a high dielectric strength. Paper withstands thermal stresses and it has sufficient mechanical strength to withstand the forces exerted on it while in operation.

Molecular structure of the cellulose is a polymer made up of chain of glucose molecules as illustrate in the Figure 2.1. These glucose molecules are linked together with glycoside oxygen bonds and Hydrogen bonds with hydroxyl (-OH) groups on the adjacent molecules are holding the cellulose fibers together.

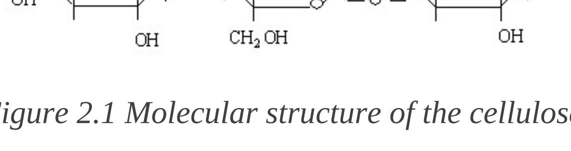


Figure 2.1 Molecular structure of the cellulose

Paper insulation is used in following parts of the Transformers

- Winding insulation
- Condenser core bushing

- To insulate conductors and cables

Figure 2.2 Paper insulation of Transformer [3]

Figure 2.2 shows how the paper insulations are used inside a power Transformer.

2.2.3 Pressboard

In instances where certain parts of a transformer are subjected to higher mechanical and electrical stresses during operation, thin cellulose paper alone may not suffice. To address this challenge, a specialized form of insulation known as pressboard is employed. Pressboard is created by stacking multiple layers of thin cellulose paper, typically in a wet stage or by bonding these layers together using a suitable adhesive. This approach results in a composite insulation material that possesses enhanced mechanical and electrical strength, allowing it to effectively handle the elevated stresses and demands within the transformer, thus ensuring its reliable and safe operation.

Pressboards are used in following applications in Transformer

- Block washers, angle washers, terminal gear cleat, supports, spacers, Yoke insulation, insulating end windings, etc.

Figure 2.3 Pressboard [3]

Figure 2.3, shows various types of pressboard which are used in Transformers.

2.2.4 Wood

Compressed laminated wood is used in Transformers as another insulation material which is made by cutting fine birch into veneers, gumming, stacking, pressing and then drying. Wood has high durability, low density, high dielectric strength, high mechanical strength and high oil absorption capability. These are widely used as supports in Transformers

2.3 Ageing of Transformer Insulation

During transformer operation, paper insulation experiences a combination of electrical, mechanical, chemical, and thermal stresses. The aging of paper insulation under these diverse stressors primarily involves the reduction in polymer chain length, a process known as chain scission. As a consequence, the dielectric properties of cellulose paper deteriorate, and its mechanical strength is compromised. This degradation eventually reaches a point where the cellulose paper can no longer serve as effective insulation. Such deterioration poses a critical risk, potentially leading to the unintended failure of transformers even under normal operational conditions.

The degradation of cellulose paper insulation is primarily attributed to three main mechanisms.

Oxidation - Cellulose contains hydroxyl groups which can be quite easily oxidized to carbonyl and carboxyl groups. This is a weakness of cellulose. This process reduces the strength of glycosidic bonds [4]. Hence, it initiates degradation reactions further such as scission of glycosidic links.

Moisture and Carbon oxides are the byproducts of oxidation process as illustrate in Figure 2.4

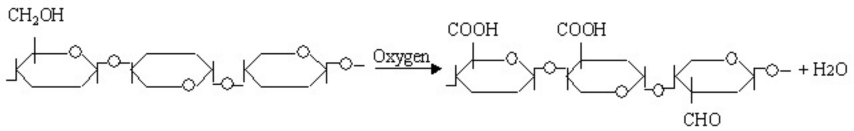


Figure 2.4 Oxidation process

Pyrolysis - Chemical structure of the cellulose tends to breakup at higher temperatures. This happens usually above the 130 0C without involvement of Oxygen and water. Free glucose molecules, moisture, carbon dioxides, organic acids and furans (a class of hydrocarbons) are the byproducts of pyrolysis degradation process. Chemical reaction happen due to pyrolysis degrading process is illustrated in Figure 2.5.

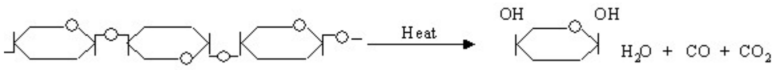


Figure 2.5 Pyrolysis degrading process

Hydrolysis - Cellulose paper insulation has very strong relationship with water which is adversely affecting on its properties. Hence, the moisture in the paper insulation is considered as the most powerful degrading agent for paper insulation.

As illustrated hydrolysis reaction in the Figure 2.6, moisture or acid cleave the glycosidic bond of cellulose polymer.

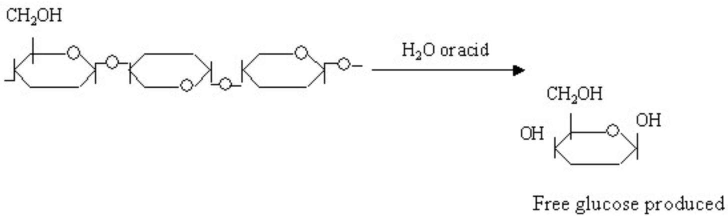


Figure 2.6 Hydrolysis process

In the context of paper insulation, water can exist in four distinct states:

- Molecules Absorbed to Surfaces: Water molecules may be absorbed and adhere to the surfaces of the paper.
- As Vapor: Water can exist in a vapor state, dispersed throughout the paper.
- As Free Water in Capillaries: Some water may be present as free water within the capillary spaces of the paper.
- As Imbibed Free Water: This refers to water that has been absorbed by the paper, penetrating its structure.

Given these different states of water within the paper insulation, it is crucial to ensure proper drying processes before the paper is put into operation. Effective drying helps to remove excess moisture and ensures that the insulation performs optimally and avoids potential issues associated with water content.

In addition to the moisture produced by ageing paper insulation itself, exposure of paper to atmosphere can also bring moisture in to the paper. Following are the main sources of water contamination in Transformer insulation.

- Residual Moisture in Thick Structure Elements
- Ageing of Cellulose and Oil
- Ingress from Atmosphere

2.3.1 Residual Moisture in Thick Structure Elements on Oil

In certain cases, thick solid insulation components like wooden and pressboard blocks may retain excessive residual moisture. These components necessitate longer drying times compared to paper and pressboard. As the transformer operates and the winding and oil temperatures increase, the residual moisture present in these thick structures gradually migrates into the oil, thereby raising the water content in the thinner insulation structure. Proper management of residual moisture in thick insulation elements is essential to avoid adverse effects on the transformer's performance.

2.3.2 Water from Cellulose paper

The degradation processes of paper insulation, which include hydrolysis, oxidation, and pyrolysis, yield a range of byproducts, among which water and furan compounds are significant. Notably, there is no direct correlation between the amount of water evolved and the degree of paper aging.

However, Figure 2.7 provides a summary of the water content produced at different levels of chain scissions, as determined through laboratory studies conducted by H.P. Moser et. Al. and others ([3], [4], [28]). According to the CIGRE brochure on moisture equilibrium and moisture migration within transformer insulation systems [5], the relationship illustrated in Figure 2.7 is considered valid for research purposes. This relationship is also confirmed by other research studies, such as those conducted by L.V. Lundgaard et.al. [1]. In this context, the initial degree of polymerization is assumed to be 1200, and it is observed that 5 chain scissions cause the degree of polymerization to drop down to 200. This data is crucial for understanding the impact of aging on paper insulation and the resulting changes in water content.

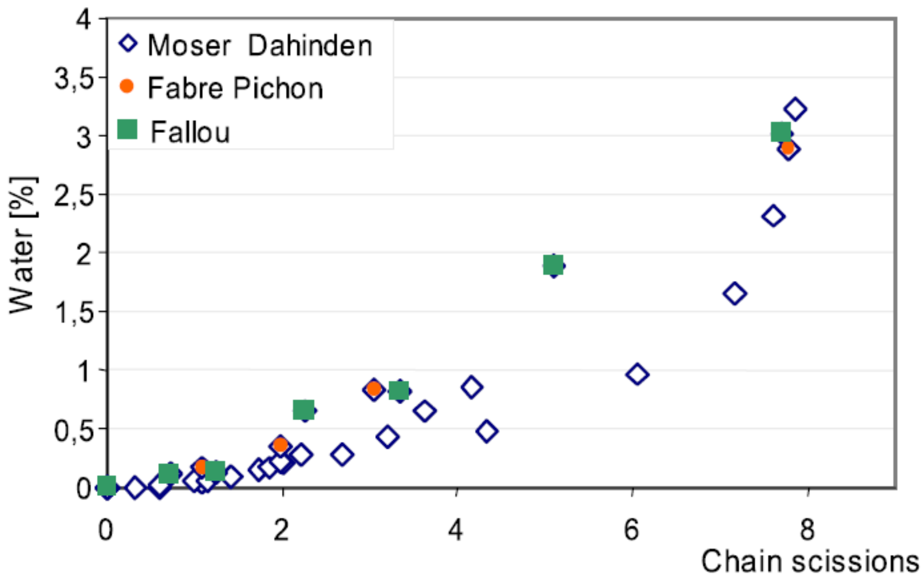


Figure 2.7 Relation between Water content and Chain scissions [5]

2.3.2 Moisture Ingress

The primary source of moisture ingress into a transformer is from the surrounding atmosphere, facilitated by three main mechanisms:

Sorption: Sorption is the process by which moisture enters the transformer when its insulation is directly exposed to the air. It involves the gradual absorption of moisture from the surrounding environment.

Molecular Flow: Molecular flow can result in moisture ingress when there is a difference in water concentration between the atmosphere and the transformer oil. This typically occurs during vacuum treatment of the transformer and is generally negligible during regular operation.

Viscous Flow: Moisture can enter the transformer through viscous flow when there is a pressure difference between the transformer and the atmosphere. This mechanism is known as viscous flow and occurs through poorly sealed joints under the influence of a pressure gradient. Potential locations for viscous flow include the top sealing of draw-lead bushings, explosion vent seals, and areas where oil leaks in the path of forced oil circulation between a transformer and its cooler. Rapid changes in pressure can lead to a significant influx of live water (rainwater) into the transformer within a short time period. Table 2-1 prepared by V. Griffin et. al.[6] shows the upper limits of water contamination due to different mechanisms for common Transformers.

Table 2-1 Water contamination due to different mechanism. Adapted from [6]

Condition		Rate of Consumption
Direct exposure insulation to air	RH = 75%, 16h, 20^{0}C	13.5 kg
	RH = 40%, 16h, 20^{0}C	8.1 kg
Water vapor molecular flow	Via sealing capillaries	1-5 g/year
	Via loosed gaskets	30-40 g/year
Viscous flow	Adequate sealing	600 g/year
	Insufficient sealing	15 g/day
Operation with open breathing		6000 g/year
Insufficient sealing drowned with rain water		200 g/hour

2.4 Mechanism of controlling the ageing agents in Transformer

There are two methods developed to reduce the direct exposure of insulation with atmosphere as given bellow.

- Silica gel breather
- Air Cell / Diaphragm

2.4.1 Silica Gel Breather

In a transformer, the oil in the main tank expands and contracts with variations in temperature. As the oil expands, it displaces air in the conservator tank, and as it contracts, it creates a vacuum that draws air back in. This cyclical process is known as "breathing" or "inhaling."

To prevent moisture from entering the transformer along with the incoming air during the breathing process, a silica gel breather is employed. The silica gel breather is connected to the breather point, and its primary function is to adsorb moisture from the air entering the conservator tank.

Silica gel is a desiccant that has a high affinity for water vapor. As air passes through the silica gel breather, the silica gel adsorbs the moisture, ensuring that dry air enters the transformer. This helps in preventing the accumulation of moisture in the transformer oil, which could otherwise lead to issues such as degradation of insulation properties and the formation of sludge. There are two types of Breathers.

In the conventional Breathers, condition of the silica gel needs to be checked regularly and replacement is required. Color of the silica gel gets changed with the absorption of moisture. Usually, blue colored dry silica gel become pink colored with the absorption of moisture. Based on the color change, the silica gel needs to be replaced manually in conventional breathers. Figure 2.8, show the conventional breather arrangement.

Figure 2.8 Conventional Breather

Maintenance free Breather is the other type and is an advanced version of the conventional Breather, where there is a heater inside the Breather, so that it can heat and dry out the silica gel when get wet to a certain level. Therefore, regular inspection on color changes and replacement are not required. Figure 2.9, shows the maintenance free breather arrangement.

Figure 2.9 Maintenance free breather

2.4.2 Breathing types

There are two types of breathing mechanisms of Transformers.

First one is free breathing mechanism where Breather is connected directly to the top of the Conservator tank via a pipe. Hence, breathing air into the Transformer will directly get contacted with insulation oil in the conservator tank. The main drawback of this mechanism is atmospheric oxygen and water will directly get contacted with oil and dissolve in oil.

In order to get rid of the drawback of free breathing system, there is an Air Cell (balloon) installed above the oil level in the conservator tank and the breather is directly connected into the Air Cell. This is called Air cell breathing mechanism. Instead of air cell rubber diaphragm installed in the middle of the conservator of some Transformers tank to avoid direct contact with atmospheric air Figure 2.10, show the Diaphragm and Air cell installed in a conservator tank.

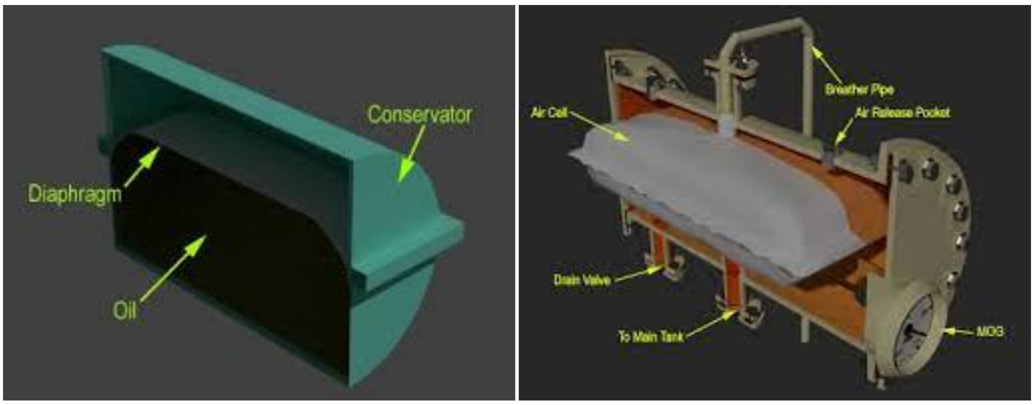


Figure 2.10 Diaphragm and Air Cell arrangement in Conservator tank

2.5 Ageing Studies of Transformers

Several studies have been performed to quantify and understand the effect of moisture, Oxygen and temperature on ageing of paper insulation [1][7][8][5][9][10][11][12][13][14][15]. Ageing of paper insulation is characterized by parameter called Degree of Polymerization. Degree of polymerization is nothing more than average number of β-D-glucopyranosyl units in cellulose polymer. It is generally accepted that, new Transformer insulation has DP of 1000 and that value reach to 200 at the end of life [1].

2.5.1 Relationship between Degree of Polymerization and the Ageing

The relation between Degree of polymerization and the ageing of paper insulation is described in following equation (*2-1*by Emsleyet. al. [16]

$$\frac{1}{DP(t)} - \frac{1}{DP(0)} = kt \qquad (2\text{-}1)$$

Where, t is ageing time in hours, DP(t) is Degree of Polymerization at time t, DP(0) is the initial Degree of Polymerization and k is Ageing factor.

Emsley, further relates the ageing rate k to temperature using the Arrhenius relationship as given in ((*2-2*).

$$k = Ae^{-Ea/RT} \qquad (2\text{-}2)$$

Where, A is Pre-Exponential factor in h^{-1}, E_a is activation energy in $Jmol^{-1}$, R is the Gas Constant in $Jmol^{-1}K^{-1}$ and T is the temperature in Kelvin.

2.5.2 Effect of Moisture on Ageing

Moisture plays a pivotal role in ageing of paper insulation. A. M. Emsley et. al.[10],L. E. Lundgaard et. al. [1], N. Lelekakis et. al. [7] and N. Lelekakis et. al.[9] have done experiments and found the value of pre exponential factor 'A' in equation ((*2-2*) at different activation energies and normalized to activation energy of 111 kJmol-1with low Oxygen levels.

Results of all of them are tabulated and then averaged as below in the Table 2-2.

Table 2-2 Summary of values of 'A' from different researches. Adapted from [1], [7], [9], [10], [26]

[7]Moisture content %	Emsley data	Lundgaard data	Lelekakis and Susa data	Lelekakis and Martin data	Average
0.5	1.07E+08	2 E+08	1.28 E+08	1.42 E+08	1.4425 E+08
1.0	3.50 E+08	-	-	-	3.5 E+08
1.6	-	-		6.8 E+08	6.8 E+08
2.0	7.80 E+08	-	-	-	7.8 E+08
2.7	-	21 E+08	-	16.5 E+08	18.75 E+08
4.0	35.0 E+08	-	-	-	35 E+08

2.5.3 Effect of Oxygen on Ageing

N. Lelekakiset.al. have done experiments on ageing of the Kraft paper and found the values of pre exponential factor 'A' in equation ((*2-2*) at different moisture and oxygen contents as tabulated in Table 2-3 [7]. For their experiment, value of activation energy was111 $kJmol^{-1}$.

Table 2-3 'A' values at different moisture contents. Adapted from [7]

	Moisture content %		
Oxygen Level	0.5%	1.6%	2.7%
Low O_2< 7000	1.28E+08	8.25 E+08	30 E+08
Medium	9.26E+08	21.9 E+08	52 E+08

7000 < O_2< 14000			
High O_2> 14000	17.4E+08	44.4 E+08	74.1 E+08

2.6 Effect of Hotspot Temperature on Transformer Ageing

Load variations in a transformer play a pivotal role in determining its operational lifespan. The fluctuation in load, whether an increase or decrease, directly influences the transformer's longevity due to its impact on the Hot Spot temperature. The Hot Spot temperature is a critical operational parameter that significantly affects the lifespan of paper insulation, thereby influencing the overall health of the transformer.

When the load on the transformer decreases, the Hot Spot temperature tends to decrease as well. Conversely, an increase in load leads to a higher Hot Spot temperature. Since temperature is a key determinant of the paper insulation's lifespan, these variations are crucial factors in shaping the overall durability and performance of the transformer.

For a comprehensive analysis of how load increments impact the transformer's lifespan, precise calculations of the Hot Spot temperature are essential. The IEEE loading guide [17] offers a set of equations explicitly designed to calculate the Hot Spot temperature under specific load conditions, as described in below sections.

2.6.1 Calculation of Hotspot Temperature

According to the IEEE loading guide [17], following equation set has been given to calculate the hot spot temperature.

The hot spot temperature has been given by ((2-3),

$$\Theta H = \Theta A + \Delta\Theta TO + \Delta\Theta H \qquad (2\text{-}3)$$

Where, ΘH is the winding hottest spot temperature

ΘA is the average ambient temperature

$\Delta\Theta$TO is the top oil temperature raise over ambient temperature

$\Delta\Theta$H is the winding hot spot raise over top oil temperature

2.6.2 Top oil temperature raise over ambient temperature

The top oil temperature raise has been given by ((2-4).

$$\Delta\Theta TO = (\Delta\Theta TO,U - \Delta\Theta TO,i)\left[1 - e^{-\frac{t}{\tau TO}}\right] + \Delta\Theta TO,i \qquad (2\text{-}4)$$

Where, ΔΘTO is the top oil temperature raise over ambient temperature

ΔΘTO,U is ultimate top oil temperature raise over ambient temperature

ΔΘTO,i is the initial top oil temperature raise over ambient temperature

ʅTO is the time constant for any load

t is the time duration in hours

2.6.3 Ultimate and initial top oil temperature raises over ambient temperature

The initial top oil temperature raise has been given by ((2-5).

$$\Delta\Theta TO,i = \Delta\Theta TO,R\,[\frac{(Ki^2R + 1)}{(R + 1)}]^n \qquad (2\text{-}5)$$

Where, ΔΘTO,i is the initial top oil temperature raise over ambient temperature

ΔΘTO,R is the top oil raise over ambient temperature at rated load

K,i is the ratio of initial load to rated load

R is the ratio of load loss at rated load to no load loss

n is the empirically derived exponent

The ultimate top oil temperature raise has been given by ((2-6)

$$\Delta\Theta TO,U = \Delta\Theta TO,R\,[\frac{(Ku^2R + 1)}{(R + 1)}]^n \qquad (2\text{-}6)$$

Where, ΔΘTO,i is the initial top oil temperature raise over ambient temperature

ΔΘTO,R is the top oil raise over ambient temperature at rated load

K,i is the ratio of initial load to rated load

R is the ratio of load loss at rated load to no load loss

n is the empirically derived exponent

2.6.4 Oil time constant

The time constant for rated load has been given by ((2-7).

$$\text{ƮTO,R} = \frac{C\Delta\Theta TO,R}{PT,R} \qquad \textit{(2-7)}$$

Where, ƮTO,R is the time constant for rated load (h)

ΔΘTO,R is the top oil raise over ambient temperature at rated load (^{0}C)

P T,R is the total loss at rated load (W)

C is the thermal capacity of the Transformer (W-h/^{0}C)

C has been given by ((2-8) for ONAN conditions and ((2-9) for ONAF condition.

$$C = 0.1323(\text{weightofcoreandcoilassemblyinkg}) + 0.0882(\text{weightoftankandfittinginkg}) + 0.3513(\text{oilquantityinl}) \qquad \textit{(2-8)}$$

$$C = 0.1323(\text{weightofcoreandcoilassemblyinkg}) + 0.1323(\text{weightoftankandfittinginkg}) + 0.5099(\text{oilquantityinl}) \qquad \textit{(2-9)}$$

Then the oil time constant has been given by ((2-10)

$$\text{Ʈ}To = \text{Ʈ}TO,R \frac{\left(\frac{\Delta\Theta TO,U}{\Delta\Theta TO,R}\right) - \left(\frac{\Delta\Theta TO,i}{\Delta\Theta TO,R}\right)}{\left(\frac{\Delta\Theta TO,U}{\Delta\Theta TO,R}\right)^{\frac{1}{n}} - \left(\frac{\Delta\Theta TO,i}{\Delta\Theta TO,R}\right)^{\frac{1}{n}}} \qquad (2\text{-}10)$$

Where, ƮTO is the oil time constant (h)

ƮTO,R is the time constant for rated load (h)

$\Delta\Theta$TO,i is the initial top oil temperature raise over ambient temperature (^{0}C)

$\Delta\Theta$TO,U is the ultimate top oil temperature raise over ambient temperature (^{0}C)

$\Delta\Theta$TO,R is the top oil raise over ambient temperature at rated load (^{0}C)

n is the empirically derived exponent

2.6.5 Winding Hotspot raise

The winding hot spot temperature raise has been given by ((2-11).

$$\Delta\Theta H = (\Delta\Theta H,U - \Delta\Theta H,i)\left[1 - e^{-\frac{t}{\text{Ʈ}w}}\right] + \Delta\Theta H,i \qquad (2\text{-}11)$$

Where, $\Delta\Theta$H is the winding hot spot temperature raise over top oil temperature (^{0}C)

$\Delta\Theta$H,U is ultimate winding hot spot temperature raise over top oil temperature (^{0}C)

$\Delta\Theta$H,i is initial winding hot spot temperature raise over top oil temperature (^{0}C)

Ʈw is the winding time constant for any load and taken as 8 minutes. (0.133h)

t is the time duration in hours

2.6.6 Ultimate and initial winding hotspot temperature raise over top oil temperature

The initial winding hot spot temperature raise over top oil has been given by ((2-12).

$$\Delta\Theta H,i = \Delta\Theta H,R \; K,i^{\,2m} \qquad (2\text{-}12)$$

Where, $\Delta\Theta H,i$ is initial winding hot spot raise over top oil temperature (^0C)

$\Delta\Theta H,R$ is winding hot spot raise over top oil temperature at rated load (^0C)

K,i is the ratio of initial load to rated load

m is the empirically derived exponent

The ultimate winding hot spot temperature raise over top oil has been given by ((2-13).

$$\Delta\Theta H,U = \Delta\Theta H,R \; K,U^{\,2m} \qquad (2\text{-}13)$$

Where, $\Delta\Theta H,U$ is ultimate winding hot spot raise over top oil temperature (^0C)

$\Delta\Theta H,R$ is winding hot spot raise over top oil temperature at rated load (^0C)

K,U is the ratio of ultimate load to rated load

m is the empirically derived exponent

2.6.7 Exponents used for temperature determination equation

According to the IEEE loading guide[17], exponents m and n have been given in the Table 2-4

Table 2-4 Exponents 'n' and 'm' values

Type of Cooling	**m**	**n**
ONAN	0.8	0.8
ONAF	0.8	0.9

2.7 Transformer Cooling fans

Transformer cooling systems are crucial components in electrical power networks, ensuring the efficient operation and longevity of transformers. Among the various cooling methods employed, forced air-cooling systems utilizing cooling fans play a pivotal role in dissipating heat generated during transformer operation. Understanding the functionality and design considerations of cooling fans is essential for optimizing transformer performance and reliability.

Transformer cooling systems can be categorized into different types based on their cooling mechanisms. These include oil-immersed cooling systems, air-cooled systems, and forced air-cooling systems. While natural convection cooling relies on the buoyancy of oil within the transformer tank, forced air-cooling systems utilize cooling fans to enhance heat transfer efficiency.

Cooling fans are integral components of forced air-cooling systems, facilitating the circulation of air around transformer components to dissipate heat effectively. By maintaining optimal operating temperatures, cooling fans prevent thermal degradation of insulation materials and ensure the reliability of transformer equipment. The proper selection, service timing and sizing of cooling fans are critical to achieving efficient heat dissipation and extending transformer service life. Design considerations for transformer cooling fans include factors such as fan size, blade design, rotational speed, and airflow capacity. These parameters directly influence the cooling effectiveness and energy efficiency of the cooling system. Advanced computational fluid dynamics (CFD) simulations and experimental studies are employed to optimize cooling fan designs and performance under various operating conditions.

CHAPTER 3 METHODOLOGY

3.1 Introduction

Paper insulation used in Transformer is a cellulose base insulation [3]. The ageing of such paper insulation can be modeled by pseudo – zero rate law equations ((*2-1*) as in Chapter 2 section 2.5.1.

Further the relationship of ageing rate k with temperature can be modeled using Arrhenius relationship as given in ((*2-2*) in Chapter 2 section 2.5.1.

Figure 3.1, illustrates the method of calculating ageing condition (DP)' of paper insulation considering dynamic behavior of the moisture, Oxygen and temperature. As shown in Figure 3.1, Pre exponential factor ('A') depends on moisture content and the Oxygen level of the Transformer. The Moisture content of the Transformer has been calculated on monthly basis. Since the paper ageing itself generates moisture, moisture generation in the Transformer is a chain reaction and hence, moisture dependency of 'A' has been modeled using exponential equation. The Oxygen level is also estimated on monthly basis and the Oxygen dependency of 'A' has been modeled using 2nd order polynomial equation. Based on those calculated moisture content and oxygen levels, the value of A has been calculated on monthly basis from the date of commissioning of Transformer till its end of life.

As shown in Figure 3.1, the Ageing rate ('k') depends on 'A' and hot spot temperature of the Transformer. Hence, hourly Hot spot temperature data of Transformers have been collected over the last 5 years and 24-hour temperature data for each month have been calculated by averaging them. Calculated averaged temperature data and 'A' values have been used to calculate ageing rate k using equation ((*2-2*) on hourly basis.

Then as per the Figure 3.1, Degree of polymerization of the Transformer has been calculated hourly basis from equation ((*2-1*) by substituting the hourly calculated 'k' values. Initial DP value has been considered as 1000 for the calculated.

In this research, DP of 200 is considered as the end of life of the paper insulation and therefore remaining life is defined as time taken to reach DP of 200 from December of 2023. In chapter 04, current ageing condition of Transformers (till end of 2023) and then remaining lifetime of the Transformers have been calculated as mentioned above by considering 200 DP as end of life of paper insulation.

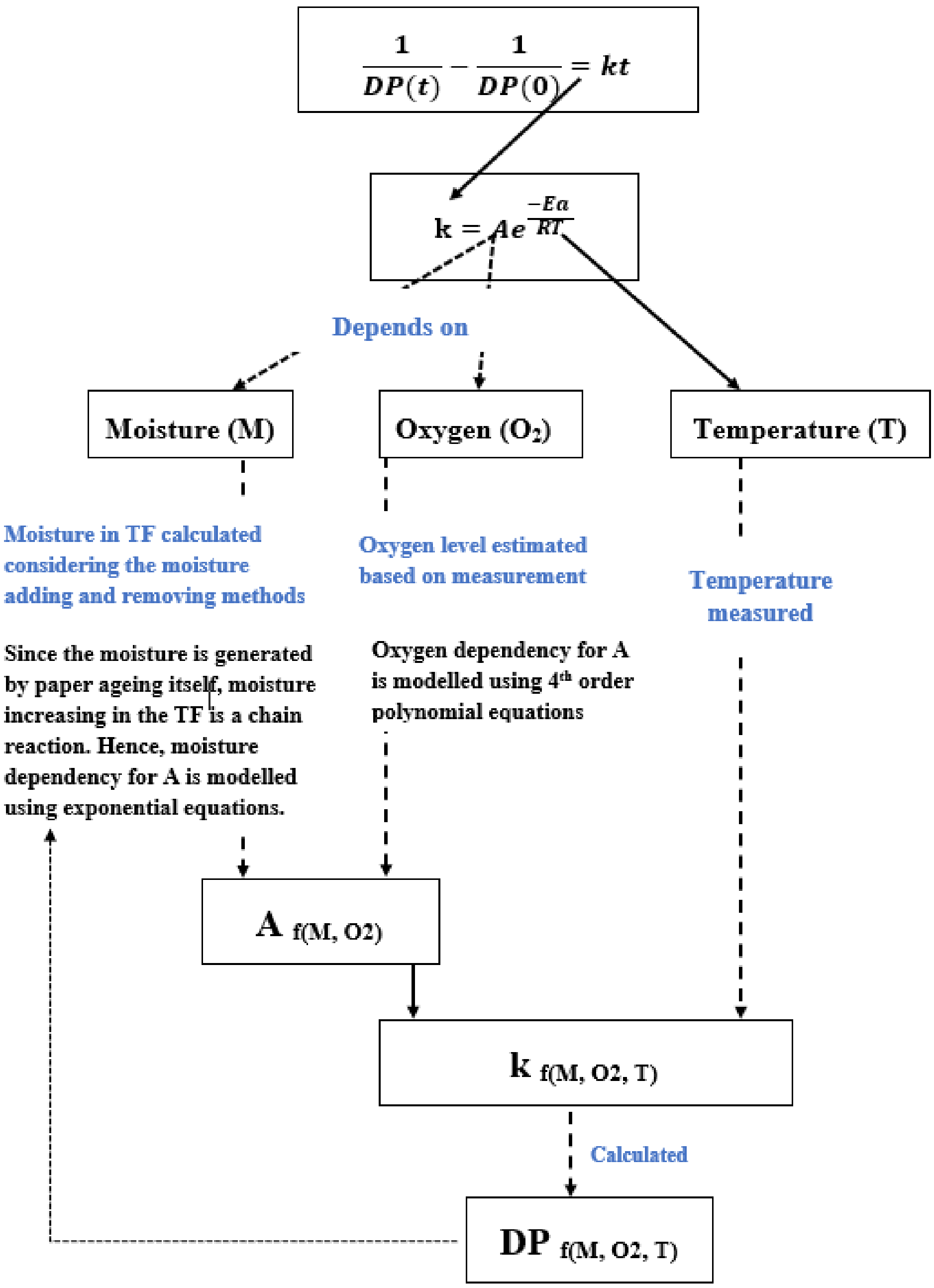


Figure 3.1 Whole calculation in graphical view

Most of the considered Transformers have been partially loaded to prevent breakdowns, and are not utilized in an optimal way. Therefore, in this research operation of Transformers at increased load was analyzed considering different cooling fan temperature settings, to eliminate the increased hot spot temperature due to increased load in order to achieve an improved lifetime.

A mathematical model was developed for life extension and load increment by finding the most effective cooling fan group temperature setting in such a way that cost is optimized over the remaining life of an ageing transformer. The mathematical model includes three sub-models, which are thermal model, transformer remaining life estimation model, and cost optimization model. For thermal model IEEE loading guide was used to calculate the hot spot temperatures at elevated loads [17] . The output, hot spot temperatures at elevated loads, were used as an input for transformer remaining life estimation calculation (DP Calculation) as shown in Figure 3.1, to calculate the new remaining life of transformer with new loading, and new cooling fan temperature settings. Finally, that output was used to find the optimum solution using the cost optimization model, which is based on NPV calculation.

3.2 Calculation of Moisture Content

As shown in Figure 3.1, Pre exponential factor (‘A’) depends on moisture content and the Oxygen level of the Transformer. Hence, calculation of moisture content is the first requirement for calculating ‘A’.

There are three methods of moisture adding into the Transformer as below,

1. Inhaling
2. Paper ageing itself
3. Through oil leaks

There are two methods of moisture removing from the Transformer

1. Oil filtering (Offline / Online)
2. Breather absorption

In order to calculate the moisture content of the Transformer, all above moisture adding and removing methods have been considered.

3.2.1 Moisture adding through inhaling

Transformer breathing system consists of Silica gel breather and it absorbs some amount of moisture in inhaling air into Transformer. Thus, moisture ingress to the Transformer insulation through breathing has been calculated by reducing the amount of moisture absorbed by breather from moisture content in inhaling air.

Calculation of moisture adding to the Transformer through inhaling is given below,

Oil volume of Transformer increases due to increase of temperature. On the other hand, oil volume of Transformer decreases at night time due to low environmental temperature and minimum loading conditions. As a result, environment air ingress into the Transformer through Silica gel breather and volume of air can be calculated using maximum and minimum temperatures, total oil volume and thermal expansion coefficient of mineral oil as explained below.

$$Oil\ volume\ change\ per\ day$$
$$=\ Oil\ volume\ X\ Thermal\ expansion\ coefficient \qquad (3\text{-}1)$$
$$X\ Daily\ temperature\ variation\ range$$

Thermal expansion coefficient of mineral oil is 7.5 X 10-4 $^{0}C^{-1}$ according to the 'Mineral Transformer oil'[18] and oil volume is mentioned in the Transformer name plate data as shown in Table 4-1.

In this study, maximum and minimum daily temperatures have been obtained from averaged monthly 24 hour temperature curve and further, average humidity and environment temperature of particular month were taken from weather sites [19][20][21].

To calculate the amount of moisture in unit volume of air at given temperature and relative humidity, the Figure 3.2 given in M. Jankovec et. al. [22], has been used.

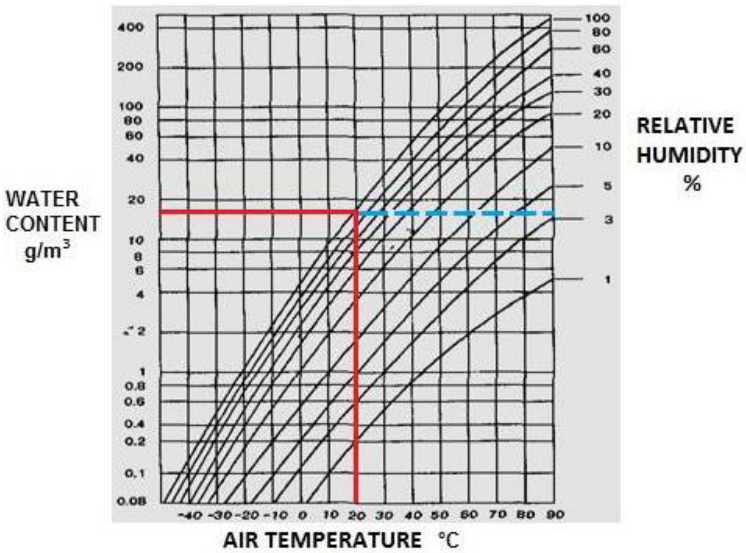


Figure 3.2 Relation among temperature, RH and water content in air [22]

Then, the amount of moisture added into the Transformer for the month has been calculated as below.

Amount of moisture inhaled into the Transformer for the month =

Volume of atmospheric air inhaled into the Transformer for the month X amount of moisture available in the unity volume of atmospheric air *(3-2)*

The amount of moisture absorbed by Breather for a month has been calculated as described below [26],

Two experiments have been carried out to identify the moisture absorption capacity of the silica gel and to estimate the monthly moisture absorption by silica gel breather.

First experiment has been carried out to identify the moisture absorption capacity and dynamic behavior at 75% relative humidity as relative humidity at Bolawatta, Madampe and Puttalam vary around 75%[19][20][21]. Results show that, the moisture absorption capacity of the silica gel is 30% of its initial weight. Moisture absorption rate of Silica gel is constant over the range from 0% to 10%.

In the 2nd experiment, actual quantity of moisture absorbed by a Silica gel breather for particular time period has been measured and result show that, total quantity of moisture absorbed during period of one year (maintenance cycle) is less than 10% of its weight. Thus, this research considered that, moisture absorbed by Silica gel breather is constant for every month of maintenance cycle.

Considering the linear behavior of moisture absorption up to 10% from experiment 1, actual moisture absorption rate has been calculated as 63 g per month for 12 kg sized breather and 31.5 g per month for 6 kg sized breather.

Then, actual amount of moisture added into the Transformer through inhaling has been calculated by using results received from above calculations as below,

$$\begin{aligned}&Actual\ moisture\ added\ into\ the\ Transformer\\ &\quad for\ the\ month\ through\ inhaling\\ &\quad = Amount\ of\ moisture\ inhaled\ into\ the\ Transformer\ for\\ &\quad the\ month - Amount\ of\ moisture\ absorbed\ by\ the\ breather\\ &\quad for\ the\ month\end{aligned} \tag{3-3}$$

3.2.2 Moisture adding through oil leaks

Another method of moisture adding into the Transformer is through oil leakages. Oil leakages details of Transformers which include numbers of oil leaks and the duration of oil leaks have been collected over the full period of operation time.

Table 2-1 in Chapter 2, section 2.3.3 prepared by V. Griffin et. al. [6], [5] gives the amount of water contamination due to different mechanisms for common Transformers. Based on the data in this table and collected oil leakage details, the amount of moisture added into the Transformer per month has been calculated as below.

$$\begin{aligned}&Total\ moisture\ adding\ due\ to\ oil\ leaks\ of\ Transformer\ per\ month\\&= No.of\ oil\ leaks\ in\ the\ month\\&* amount\ of\ moisture\ added\ from\ particular\ leak\ per\ day\\&* No.of\ days\ in\ the\ month\end{aligned} \quad (3\text{-}4)$$

3.2.3 Moisture adding through paper ageing

Paper insulation ageing itself generates moisture. Figure 2.7 in Chapter 2, section 2.3.2 summarized the water content produced by the different levels of chain scissions based on laboratory studies performed H.P. Moser et. al. [3][4][27]. Data points of this Figure 2.7 has been used to derive set of equations to get amount of moisture generated by paper ageing.

These results are accurate at higher DP values (DP > 350). In order to get better estimation at lower DP values, experiment data of J Fabre et. al. [4] and Lungard et. al. [1] were considered. Then, another set of equations have been derived to get amount of moisture generated by paper ageing at lower DP values (DP < 350).

By using relevant equation at particular DP values, amount moisture added through paper ageing has been calculated on monthly basis.

3.2.4 Moisture removing by oil filtering

Main moisture removing method is the oil filtering. This includes both online and offline oil filtering. Oil filtering details of Transformers which include the type of oil filtering and the duration of oil filtering have been collected over the full span of operation time.

The amount of moisture that is removed by online oil filtering per day was taken from Paul Koestingeret. al. [23] comparison of drying rates by different drying technologies. Then, based on these data, the amount of moisture removed by oil filtering per month has been calculated as below, The amount of moisture removed by oil filtering per month = Numbers of oil filtering days in the month * amount of moisture removing per day by relevant type of oil filtering

3.2.5 Monthly moisture content calculation

Considering all moisture adding and removing methods discussed above, the total amount of moisture added into the Transformer for particular month has been calculated as below,

$$\begin{aligned} &Moisture\ added\ into\ the\ Transformer\ for\ the\ month \\ &= (Moisture\ added\ through\ inhaling \\ &+ Moisture\ generated\ through\ ageing \\ &+ Moisture\ came\ from\ oil\ leakages) \\ &- (Moisture\ removed\ through\ offline\ oil\ filtering \\ &+ Moisture\ rmoved\ through\ online\ oil\ filtering) \end{aligned} \quad (3\text{-}5)$$

Moisture which is already available in the Transformer is calculated based on the last month's moisture content and by adding it to the above added amount, the total amount of moisture that is present in the month has been calculated as below,

$$\begin{aligned} &Moisture\ amount\ for\ the\ month \\ &= (Moisture\ content\ of\ previous\ month \\ &* Paper\ weight\ of\ the\ Transformer) \\ &+ Moisture\ added\ into\ the\ Transformer\ for\ the\ current\ month \end{aligned} \quad (3\text{-}6)$$

Then, the moisture content for the month is calculated on monthly basis as below,

$$\begin{aligned} &Moisture\ content\ at\ end\ of\ the\ month \\ &= \frac{Moisture\ amount\ for\ the\ month}{Paper\ weight\ of\ TF} * 100 \end{aligned} \quad (3\text{-}7)$$

Moisture content calculation is shown in flow chart in Figure 3.3. Initial DP has been taken as 1000. The moisture generated by paper ageing have been calculated by using one set of equations at above 350 DP values and another set of equations at below 350 DP values. Then moisture adding through inhaling, through oil leaks and previous months moisture content of the Transformer and moisture removing from oil filtering were taken into account for calculation of total amount of moisture available in the Transformer paper insulation for a particular month. Dividing that amount by the paper weight of the Transformer, the moisture content of the Transformer for that particular month has been calculated. The same calculation is repeated on monthly basis till DP reach to 200.

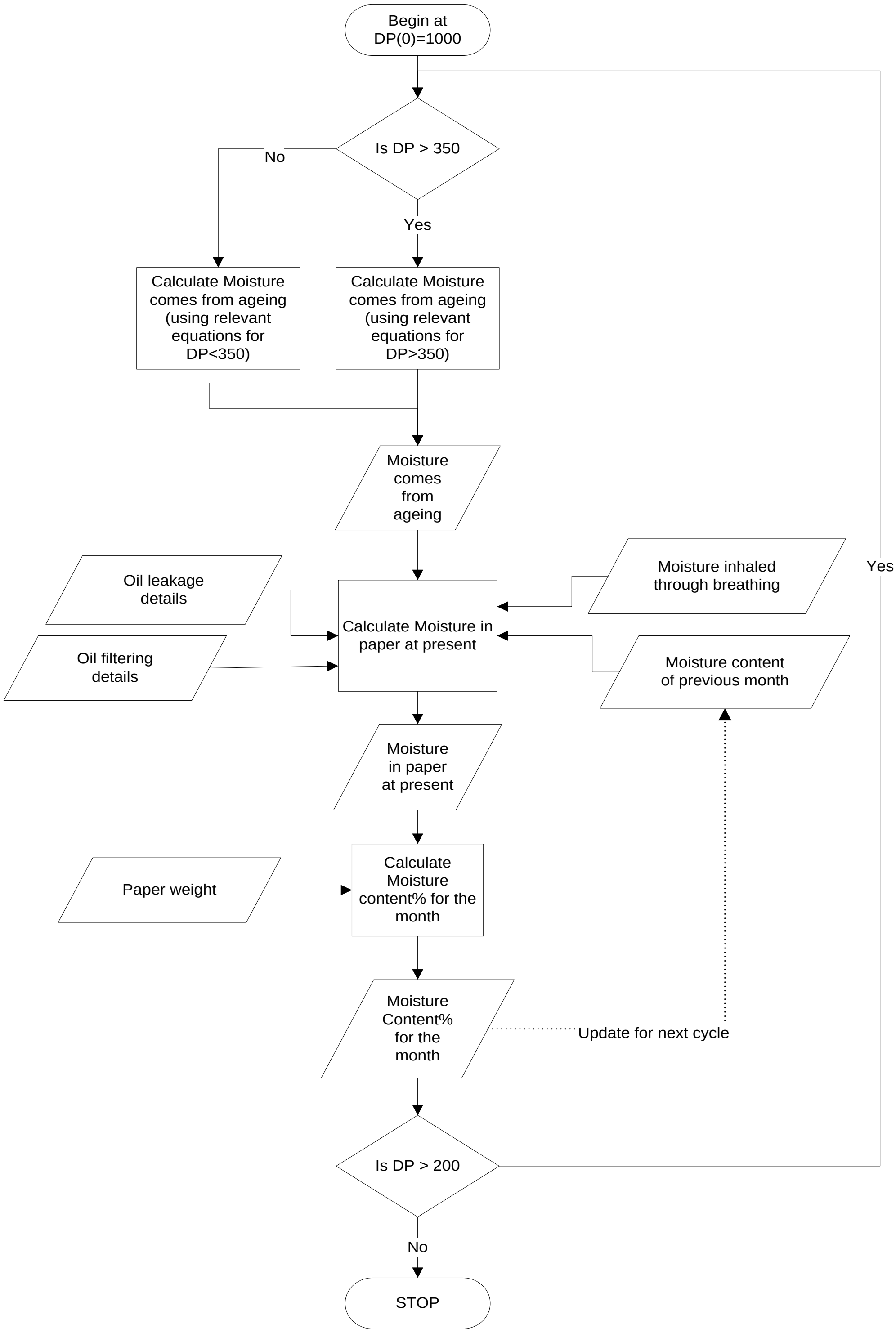


Figure 3.3 Moisture content calculation in flow chart [26]

3.3 Estimation of Oxygen Level

As shown in Figure 3.1, Pre exponential factor (‘A’) depends on moisture content and the Oxygen level of the Transformer. Since moisture content has been calculated, the 2nd requirement for the calculation of ‘A’ is the estimation of Oxygen level.

All these selected Transformers are free breathing Transformers. Therefore, it was expected that, all are operating at Oxygen higher level as per the level definition in Table 3-1, which was defined by N. Lelekakis et. al.[7].

Table 3-1 Definition of Oxygen levels [7]

Oxygen range (ppm)	Oxygen level
$O_2 < 7000$	Low
$7000 < O_2 < 14000$	Medium
$O_2 > 14000$	High

Dissolve Gas analysis tests have also been carried out on some selected Transformers and the verified that those are operated at higher Oxygen level. Refer Figure 4-1.

Since, oil filtering (which is along with oil degassing) is done time to time on these Transformers, followings were assumed,

- Transformer is assumed to be at low Oxygen level during the period from the day of oil filtering till Transformer inhaled ambient air equal to half volume of oil volume.
- Transformer is assumed to be at medium Oxygen level during the period from the Transformer inhaled ambient air equal to half volume of oil volume till full volume of oil volume.
- Transformer is assumed to be at high Oxygen level once the Transformer inhaled ambient air equal to full volume of oil volume and above.

Based on above assumptions, Oxygen levels of Transformers have been decided on monthly basis from the date of Transformer energization till its end of life.

3.4 Calculation of Pre-Exponential Factor, ‘A’

Since, the moisture content and Oxygen levels have been calculated on monthly basis, A can be calculated on monthly basis.

As tabulated in Table 2-3 in Chapter 02, section 2.5.3, [7][1][8][10][9][26] have presented experimented values of ‘A’ at different moisture contents and Oxygen levels. In this research, pre-exponential factor A at different moisture and Oxygen levels have been calculated reference to that of 1.28 X 10^{08} h^{-1} at low Oxygen and 0.5% moisture content.

Table 3-2 illustrates the method of calculating MFm, MFom and MFoh reference to low Oxygen and 0.5 moisture content.

Table 3-2 Multiplication factor calculations

	Moisture content %		
Oxygen Level	0.5%	1.6%	2.7%
Low $O_2 < 7000$	1.28E+08	8.25 E+08	30 E+08
Medium $7000 < O_2 < 14000$	9.26E+08	21.9 E+08	52 E+08
High $O_2 > 14000$	17.4E+08	44.4 E+08	74.1 E+08

Multiplication factors have been calculated considering the absorbed moisture where,

$$\textit{Absorbed Moisture Content} = \textit{Moisture content of paper} - 0.5 \quad (3\text{-}8)$$

3.4.1 Calculation of Multifaction Factor of ‘A’ for Moisture, MFm

MFm has been calculated at ‘x%’ absorbed moisture content as below,

$$MFm\ for\ x\%\ Absorbed\ moisture\ content = \frac{\text{A at x\% absorbed moisture}}{\text{A at 0\% absorbed moisture}} \qquad (3\text{-}9)$$

Similarly, MFm has been calculated for different moisture contents and then by using those values an equation was derived.

3.4.2 Calculation of Multifaction Factor of 'A' for Moisture at Medium Oxygen Level, MFom

MFom has been calculated at 'x%' absorbed moisture content as below,

$$\text{MFom for x\% absorbed moisture content} = \frac{\text{A at x\% absorbed moisture and medium oxygen level}}{\text{A at x\% absorbed moisture and low oxygen level}} \qquad (3\text{-}10)$$

Similarly, MFom has been calculated for different moisture contents and then by using those values an equation was derived.

3.4.3 Calculation of Multifaction Factor of 'A' for Moisture at High Oxygen Level, MFoh

MFoh has been calculated at 'x%' absorbed moisture content as below,

$$MFoh\ for\ x\%\ Absorbed\ moisture\ content = \frac{\text{A at x\% absorbed moisture at oxygen high level}}{\text{A at x\% absorbed moisture at oxygen low level}} \qquad (3\text{-}11)$$

Similarly, MFoh has been calculated for different moisture contents and then by using those values an equation was derived.

3.4.4 Monthly Calculation of Pre-Exponential Factor, 'A'

Based on the calculated moisture content and oxygen level of each month, 1.28 X 10^{08} h^{-1} has been multiplied by relevant multiplication factors to calculate the 'A' on monthly basis.

3.5 Calculation of Ageing Rate, 'k'

The value of k has been calculated hourly by using the equation ((*2-2*) and the calculated 'A' values as below,

$$\mathrm{k} = Ae^{\frac{-Ea}{RT}}$$

Where, E_a = 111 $kJmol^{-1}$,

R = 8.3145 $Jmol^{-1}K^{-1}$

T = Hot spot temperature + 273 K

Since, hourly temperature data is available the 'k' has also been calculated on hourly basis from the day of Transformer energization till end of its lifetime.

3.6 Calculation of 'DP' and ageing estimation

Equation ((*2-1*) and above calculated 'k' values have been used for the calculation of DP as below,

$$\frac{1}{DP(t)} - \frac{1}{DP(0)} = kt$$

$$\mathrm{DP(t)} = \frac{1}{\left(kt + \frac{1}{DP(0)}\right)}$$

Since, 'k' has been calculated on hourly, DP has also been calculated on hourly basis. As described in the Chapter 2, DP is considered as the ageing of paper insulation and hence, ageing of Transformer too.

Calculation of DP is represented graphically by flow chart in Figure 3.4. Based on the oxygen levels and Moisture content of the Transformer, the value of 'A' has been calculated using relevant multiplication factors at different Oxygen levels. Then with the use of Hot spot temperatures, the value of 'k' has been calculated and finally DP value has been calculated with the use of calculated hourly 'k' values and previous hour DP value. Same calculation has been repeated on hourly basis till DP reach to 200.

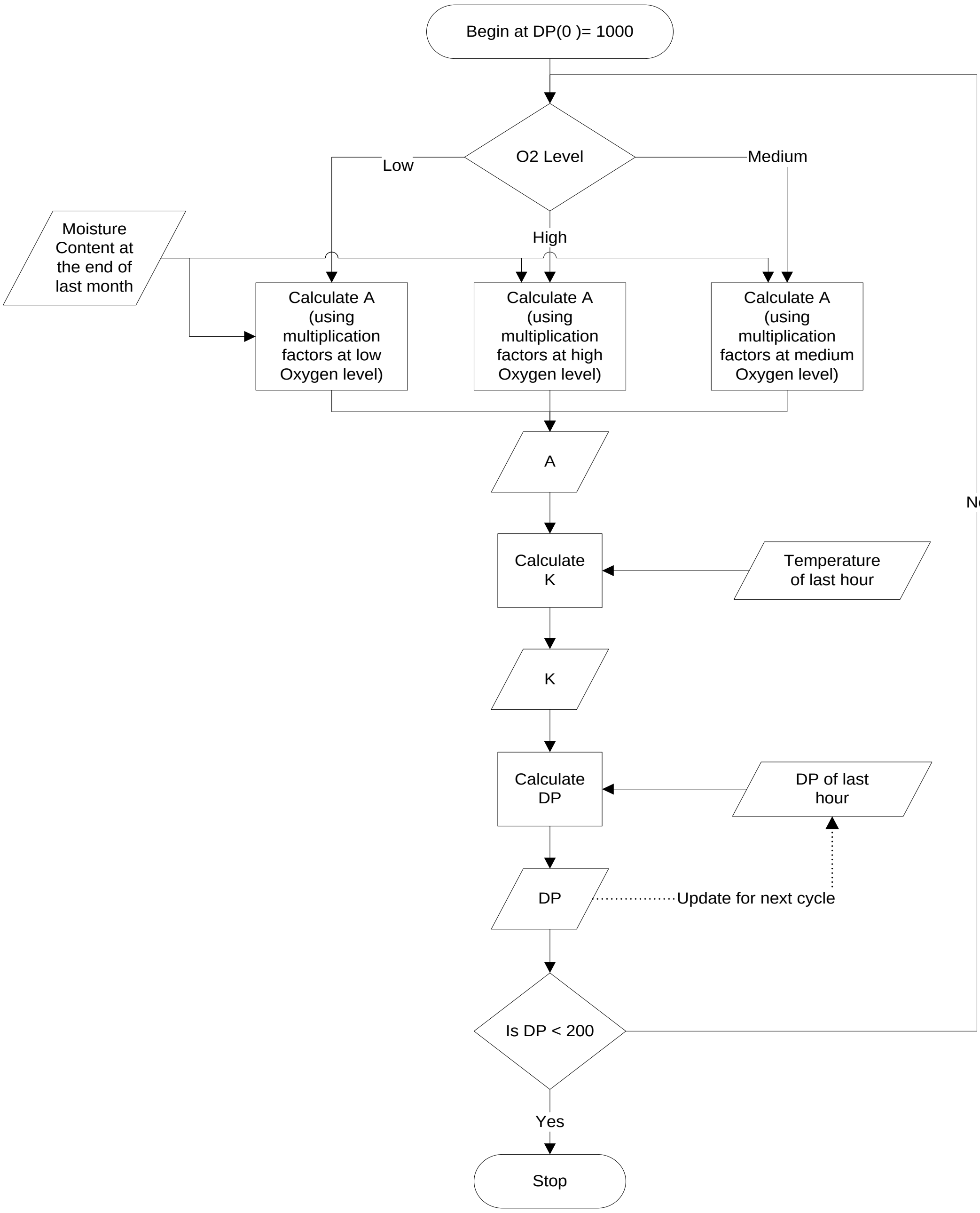


Figure 3.4 DP calculation in flow chart

3.7 Remaining lifetime estimation

Calculation explained in section 3.6, has been continued till DP reach to 200 which is the end of life of paper insulation as well as the end of life of Transformer. Then, the gap between 2024 and year on which DP becomes 200 is taken as the remaining lifetime of Transformers in years.

3.8 Development of the Mathematical Model

Most ageing transformers are partially loaded, and not optimally utilized. If the load increases, hot spot temperature will rise, resulting in accelerated ageing. On the other hand, while increasing the load if we reduce the cooling fan temperature settings (i.e. increasing the running time of the cooling fans), it will increase the loading capability, and the transformer life. However, there is an energy loss due to increase of the loading, and extra utilization of fans. Thus, it is required to optimally utilized the cooling fan group settings in such a way that loading and the lifetime of ageing transformers are improved. An optimization model was derived to attain that objective.

3.8.1 Overview of the Mathematical Model

The mathematical model overview is shown in Figure 3.5, and there are 3 sub models namely thermal model, transformer remaining life estimation model, and cost estimation model.

The core input for this model is the load curve, systematically incremented by 5% in each cycle. The output, in turn, offers a valuable synthesis of optimal combinations encompassing fan group temperature settings, improved loading percentages, and the enhanced lifetime of the transformer under the optimized settings.

In essence, the model delineates the most effective cooling fan configurations and corresponding loading strategies that not only maximize effectiveness of fan groups but also extend the overall lifespan of ageing transformers. By iteratively refining the fan group temperature settings and load, the model facilitates the identification of the optimal configuration that strikes a balance between enhanced loading, efficient cooling, and the prolonged life expectancy of the transformer. This outcome contributes significantly to the strategic and sustainable utilization of transformers, aligning operational parameters for both performance optimization and longevity.

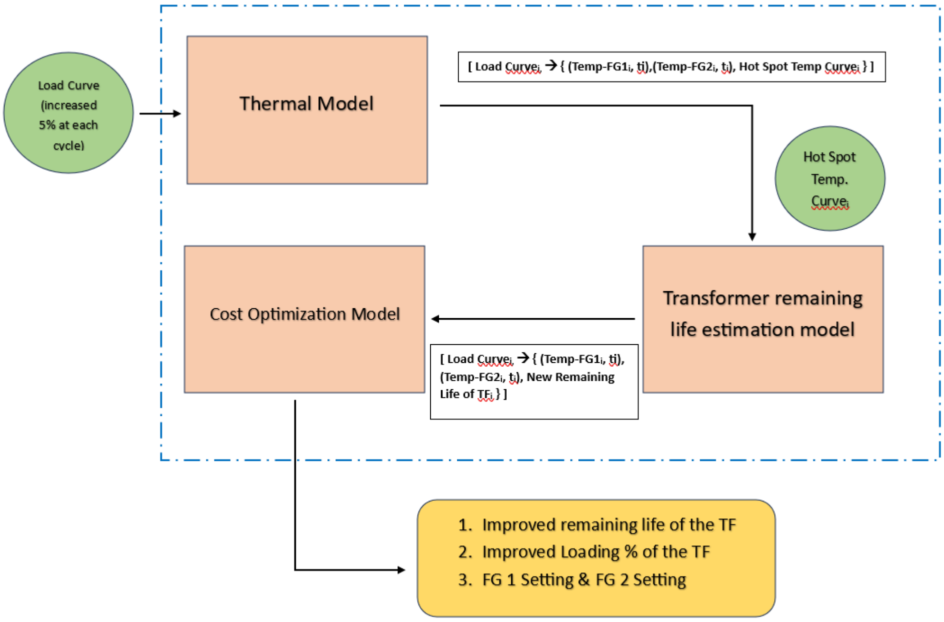


Figure 3.5 Mathematical Model Overview

3.8.2 Thermal Model

The thermal model, illustrated in Figure 3.6, serves as the foundational sub-model with a primary objective — to derive the 24-hour hotspot temperature curve for the transformer. This is achieved through a systematic exploration of diverse fan group temperature settings and the corresponding runtimes of cooling fans. The iterative process involves adjusting these settings to accommodate various load curves, each incrementally increased by 5%. The ultimate outcome of this thermal model is the comprehensive 24-hour hotspot temperature curve, intricately detailing the thermal response of the transformer under different loading scenarios. To calculate hotspot temperature under different loadings IEEE transformer loading guidelines are used [17].

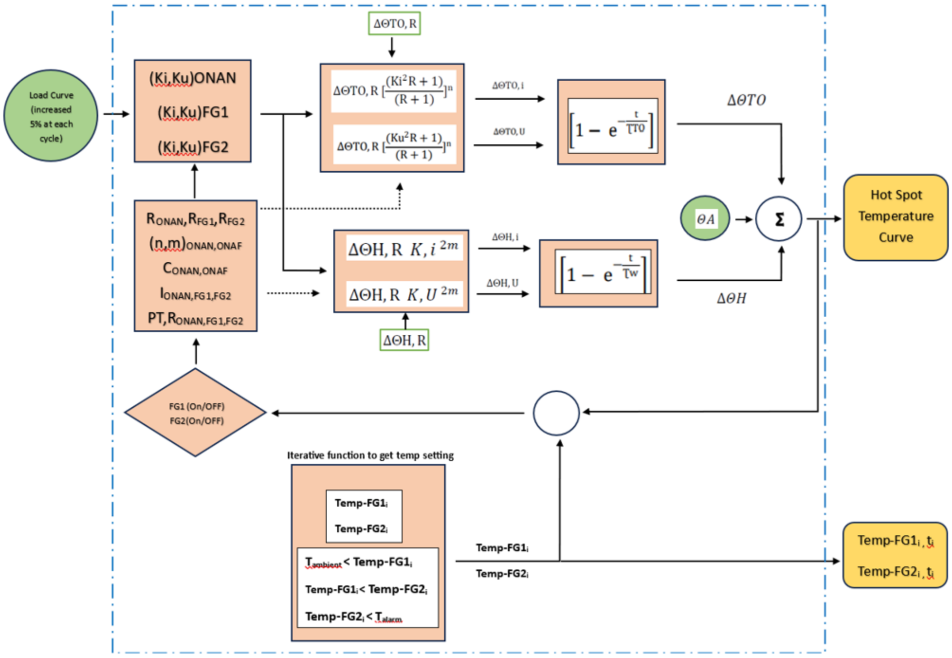


Figure 3.6 Thermal Model

3.8.2.1 Calculation of Hotspot Temperature Parameters

Calculation Hot spot Temperature parameters required Factory Acceptance Test data of the Transformers. However, FAT reports have not been available for any of these studied Transformers. Therefore, FAT reports of selected other Transformers from different venders having similar capacity and voltage ratios have been analyzed to get average values for the calculations.

Following data have been averaged and taken for the calculations

- No load loss
- Load loss at ONAN cooling condition
- Load loss at ONAF cooling condition
- Top oil temperature raise at rated load
- Hot spot temperature raise over top oil at rated load

3.8.2.1.1 Calculation of Ratio of load loss at rated load to no load loss (R)

As described in Chapter 2, section 2.6.3, R is calculated as below,

R = Load loss at rated load / No load loss

R has been calculated for all three cooling methods which are ONAN, ONAF Fan group 1 and ONAF Fan group 2 by taking relevant load loss at rated load. Load loss data were taken from averaged data as described.

3.8.2.1.2 Calculation of Thermal Capacity of Transformers (C).

From equations ((2-8), ((2-9) and Oil quantity and Transformer weight data, which available on the name plate details of the Transformers, Thermal capacity of Transformers have been calculated for ONAN and ONAF cooling conditions as below.

For ONAN

$$\begin{aligned} C = 0.1323(&\text{weight of core and coil assembly in kg}) \\ &+ 0.0882(\text{weight of tank and fittingin kg}) \\ &+ 0.3513(\text{oil quantity in l}) \end{aligned}$$

For ONAF

$$\begin{aligned} C = 0.1323(&\text{weight of core and coil assembly in kg}) \\ &+ 0.1323(\text{weight of tank and fitting in kg}) \\ &+ 0.5099(\text{oil quantity in l}) \end{aligned}$$

3.8.2.1.3 Calculation of oil time constant for rated load (ƮTO,R)

Calculation of ƮTO,R for Transformers for ONAN and ONAF cooling conditions have been calculated as shown below using averaged FAT data and above calculated R and C values from ((2-7) as below.

$$\text{ƮTO, R} = \frac{\text{C}\Delta\Theta\text{TO, R}}{\text{PT, R}}$$

3.8.2.1.4 Ki and Ku values

Calculation of Ki and Ku values, require the load data of the Transformers.

24 hours load data of Transformers have been collected over the last three years of time in operation. Load data of first week of each month have been collected. Then, average 24-hour loads have been calculated for each Transformer. Since the intention is to study the load increasing capability, averaged loads were considered for the calculations of Ki and Ku parameters.

Then, Ki and Ku have been calculated on hourly basis as below by taking the current load as below.

Ki = Load of last hour / Rated load

Ku = Load of current hour / Rated load

3.8.2.1.5 Calculation of Top oil temperature raise at initial load and ultimate load

Based on the calculated values in section 3.8.2.1.1 and 3.8.2.1.4, Top oil temperature raise at initial load and ultimate loads have been calculated as below using equations ((2-5) and ((2-6). Value for n has been taken from the Table 2-4.

$$\Delta\Theta TO,i = \Delta\Theta TO,R\,[\frac{(Ki^2R+1)}{(R+1)}]^n$$

$$\Delta\Theta TO,u = \Delta\Theta TO,R\,[\frac{(Ku^2R+1)}{(R+1)}]^n$$

3.8.2.1.6 Calculation of oil time constant at particular load (ƮTO).

ƮTO has been calculated as below using ((2-10) and the calculated values in section 3.8.2.1.5 and 3.8.2.1.3.

$$ƮTo = ƮTO,R\,\frac{\left(\frac{\Delta\Theta TO,U}{\Delta\Theta TO,R}\right) - \left(\frac{\Delta\Theta TO,i}{\Delta\Theta TO,R}\right)}{\left(\frac{\Delta\Theta TO,U}{\Delta\Theta TO,R}\right)^{\frac{1}{n}} - \left(\frac{\Delta\Theta TO,i}{\Delta\Theta TO,R}\right)^{\frac{1}{n}}}$$

3.8.2.1.7 Calculation of Top oil temperature raise at particular load

Then, the Top oil temperature raise has been calculated using ((2-4) as below.

$$\Delta\Theta TO = (\Delta\Theta TO,U - \Delta\Theta TO,i)\left[1 - e^{-\frac{t}{ƮTO}}\right] + \Delta\Theta TO,i\Delta\Theta TO$$

3.8.2.1.8 Calculation of Hot spot temperature raise over top oil at initial and ultimate loads

Hot spot temperature raise over top oil at initial and ultimate loads have been calculated using equations ((2-12) and ((2-13) as below. Value of m has been taken from Table 2-4.

$$\Delta\Theta H,i = \Delta\Theta H,R\;K,i^{\,2m}$$

$$\Delta\Theta H,u = \Delta\Theta H,R\;K,u^{\,2m}$$

3.8.2.1.9 Hot spot temperature raise over top oil at particular loads

Hot spot temperature raise over top oil at particular load has been calculated using ((2-11) as below.

$$\Delta\Theta H = (\Delta\Theta H, U - \Delta\Theta H, i)\left[1 - e^{-\frac{t}{\tau w}}\right] + \Delta\Theta H, i$$

Here, t is 1 as hourly load data is available and τw is 8 minutes according to the IEEE loading guide [17].

3.8.2.1.10 Hot spot temperature raise over ambient

Finally, the Hot spot temperature raise over ambient has been calculated using ((2-3) as below,

$$\Theta H = \Theta A + \Delta\Theta TO + \Delta\Theta H$$

Here, ΘA is the average ambient temperature and it was taken from weather reports of Madampe and Puttalam[19][20].

The same calculation has been used in the thermal model to get the Hot spot temperature curve.

During the calculation it was assumed that the cooling method will not be changed during one hour period. Based on the present hour's calculated hot spot temperature, the cooling method for the next hour has been decided with the collected Fan group operating settings of these Transformers.

3.8.3 Transformer Remaining Life Estimation Model

The transformer remaining life estimation model is shown in Figure 3.7, and the output of the thermal model, the hotspot temperature curve will be used as an input to this model. This model will deliver new transformer life for all the combinations of load, fan settings, and hot spot temperature curves.

The calculation of remaining life of transformer starting from the date of energization was done based on collected historic data as per the calculations explained in section 3.6, until January 2024, which is considered as the base year. From those calculations, DP values, moisture percentage in paper, Oxygen level inside transformer at base year is taken, and used as the input along with hotspot temperature curve from thermal model to obtain the new remaining life of the transformer with new load, and fan group temperature settings.

In the iterative function, the maximum transformer life is assumed as 50 years.

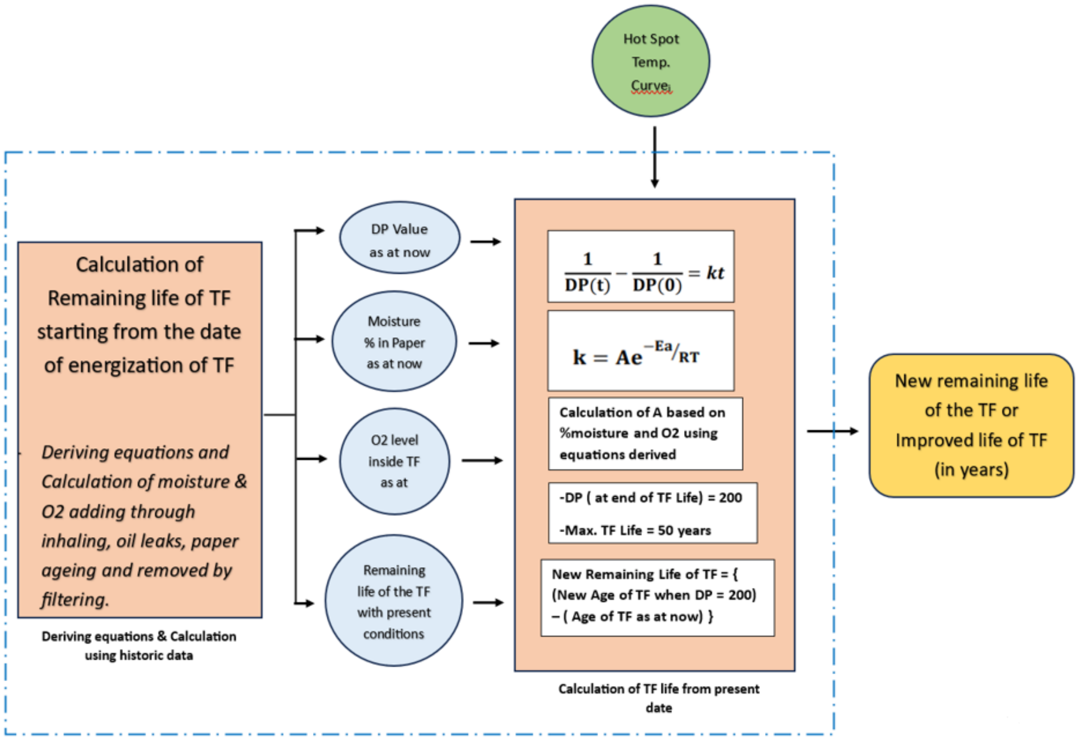


Figure 3.7 Transformer Remaining Life Estimation Model

3.8.4 Cost Optimization Model

There will be many combinations of transformer loadings, cooling fan group temperature settings, and new lifetime of transformers as output of the transformer life estimation model after iterations of the model. Thus, it is required to find the optimum solutions out of all the combinations. Therefore, the main objective of the cost optimization model is to find the most economically viable solution from the output of thermal and ageing calculation models.

The model overview is shown in Figure 3.8. There are both costs and benefits of the proposed methodology to increase the remaining life of the transformers. Increase in loads will increase the load losses, while increase in run time of the cooling fans will increase auxiliary losses, and running costs. Therefore, in this model cost of additional auxiliary losses, additional load losses, and running costs are considered as major costs. Cost saving due to deferred replacement cost due to improved lifetime of transformer, and cost saving due to increased loads are considered as benefits. In order to find the net benefit NPV calculation was performed considering costs and benefits, and thereby the most economically viable solution is identified.

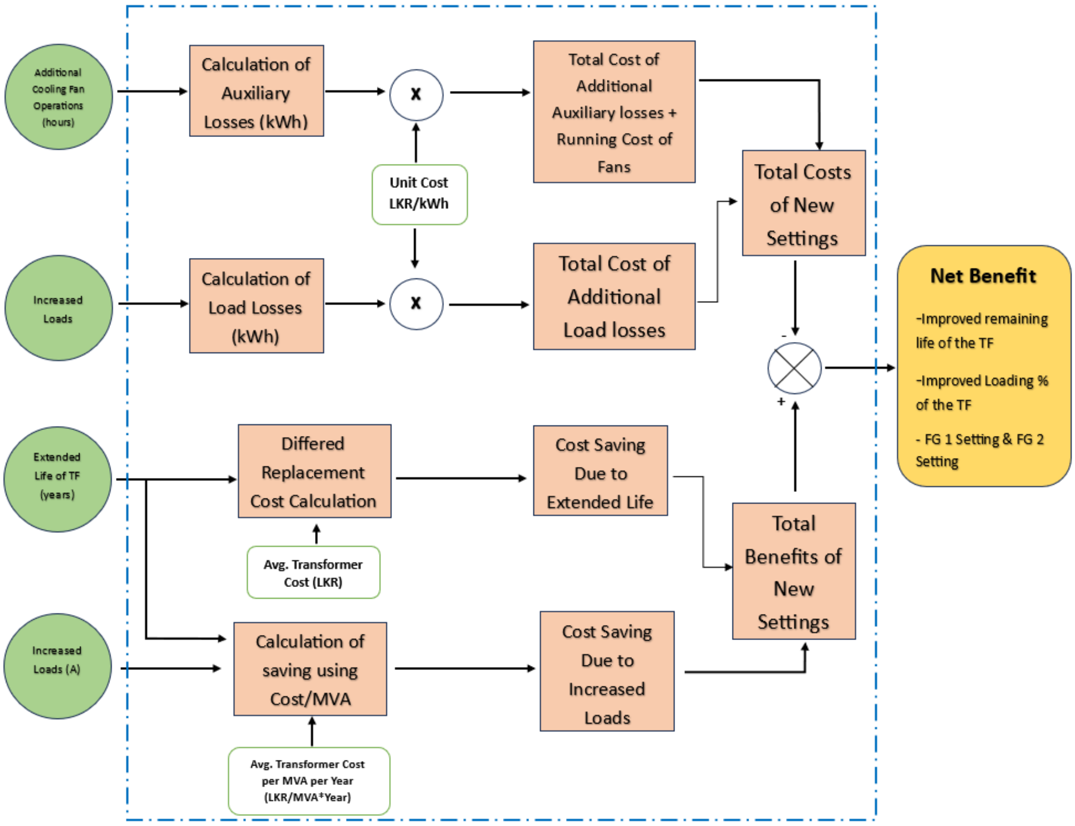


Figure 3.8 Cost Optimization Model

3.8.4.1 Calculation of Auxiliary Losses

Auxiliary losses are due to cooling fan operations, and due to increase in the runtime of cooling fans there is an additional auxiliary losses.

$$Auxiliary\ Loss\ (kWh) = Run\ time\ of\ cooling\ Fan\ Group\ 1\ \&\ Fan\ Group\ 2\ X\ power\ of\ a\ fan\ (kW)\ \ X\ number\ of\ cooling\ fans \qquad (3\text{-}12)$$

Current unit cost (Rs/kWh) of Sri Lanka is used calculate the auxiliary loss cost.

Running cost of the cooling fans are also considered when deciding the optimized solution.

3.8.4.2 Calculation of Load Losses

Load losses (Cu losses) are due to current (load) flowing through the transformer winding, and due to increase in load there is an additional load losses .

$$Load\ Loss\ (kWh) = \sum((Loadh)2\ x\ \ Transformer\ winding\ resistance) \quad \textit{(3-13)}$$

Current unit cost (Rs/kWh) of Sri Lanka is used calculate the load loss cost.

3.8.4.3 Calculation of Saving due to Increased Load

Improvement in loading of the transformer can save purchasing another MVA capacity transformer, which will be a saving to the utility. This can be reflected through the following equation.

$$\text{Previous Loading cost} = \sum\left(\sqrt{3}\ X\ Transformer\ Secondary\ Voltage\ X\ Load\right)X\ (Average\ MVA\ cost\ of\ Transformer)\ X\ 30\ X\ Lifetime\ of\ Tranformer\ X\ \ Unit\ Cost \quad \textit{(3-14)}$$

$$\text{New Loading cost} = \sum\left(\sqrt{3}\ X\ Transformer\ Secondary\ Voltage\ X\ Load\right)X\ (Average\ MVA\ cost\ of\ Transformer)\ X\ 30\ X\ New\ Lifetime\ of\ Tranformer\ X\ \ Unit\ Cost \quad \textit{(3-15)}$$

$$\text{Saving Due to Increased Loads} = \text{NPV}(\text{New Loading cost, New Lifetime}) - \text{NPV}(\text{Previous Loading cost, Previous Lifetime}) \quad \textit{(3-16)}$$

3.8.4.3 Calculation of Differed Replacement Cost

It will delay the purchase of a new transformer when the transformer lifetime is increased. Therefore, there will be a saving from the differed cost. It will be calculated as follows;

$$\text{Previous Replacement Cost} = \frac{Average\ Transformer\ Cost}{(1+Dicount\ rate)^{(previous\ life\ time+1)}} \quad (3\text{-}17)$$

$$\text{New Replacement Cost} = \frac{\text{Average Transformer Cost}}{(1+Dicount\ rate)^{(New\ life\ time+1)}} \quad (3\text{-}18)$$

Saving due to differed replacement cost =

$$Prev. Replacement\ Cost - New\ Replacement\ Cost \quad (3\text{-}190$$

CHAPTER 4 LIFETIME ESTIMATION OF AGEING POWER TRANSFORMERS

4.1 Transformer Details under the Scope

For the study, three Transformers in Transmission Grid Substations (GS) have been selected. The selected Transformers are in three Grid Substations namely Madampe and Puttalam and they are named as Madampe TF02, Puttalam TF01 and Puttalam TF02.

Details of Transformers taken for the study are tabulated in Table 4-1 and according to the tabulated details, all are in same capacity, same voltage ratio and free breathing Transformers. However, breather sizes and the oil weights are different.

Table 4-1 Details of Transformers

Details	Madampe TF02	Puttalam TF01	Puttalam TF02
Commissioned year	1994	1994	1994
Capacity at ONAF (MVA)	31.5	31.5	31.5
Capacity at ONAN (MVA)	23	23	23
Oil weight (kg)	16,500	15,300	15,300
Oil Volume (m^3)	18.54	17.19	17.19
Free Breathing / Air Cell	Free Breathing	Free Breathing	Free Breathing
Breather size (Silica gel weight kg)	12	12	12

4.2 Calculation of Moisture Content

As shown in Figure 3.1, Calculation of Pre exponential factor (‘A’) is the first aging factor to be calculated under the ageing calculation of paper insulation. According to the Figure 3.1, 'A' depends on moisture content and the Oxygen level of the Transformer. Hence, calculation of moisture content is the first required parameter for calculating 'A'. There are three methods of moisture adding into the Transformer as below,

1. Inhaling

2. Paper ageing itself

3. Through oil leaks

There are two methods of moisture removing from the Transformer

4. Oil filtering (Offline / Online)

5. Breather absorption

In order to calculate the moisture content of the Transformer, all above moisture adding and removing methods have been considered.

4.3 Estimation of Moisture Absorption of Silica Gel in Breathers

As described in section 3.2.1 in method Chapter, an experiment has been carried out in order to verify the moisture absorption capacity of Silica gel. Moisture absorption characteristics of Silica gel is generally given by 'An evaluation of Silica gel for humidity control in display cases'[24].

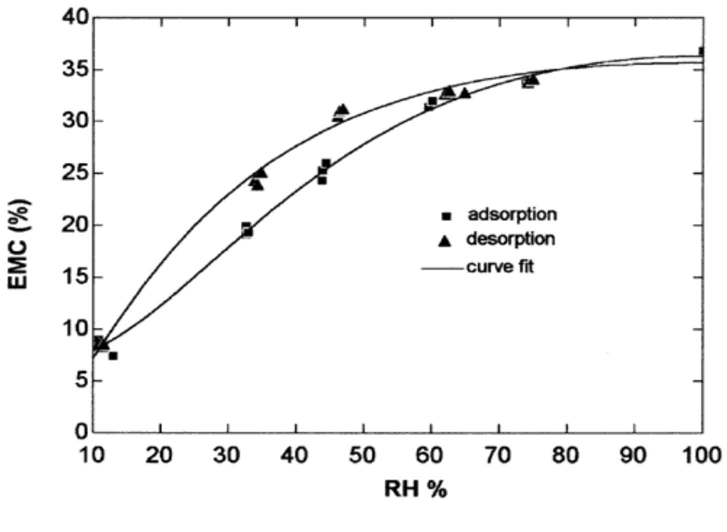


Figure 4.1 Moisture absorption characteristics by Silica gel in general

According to the Figure 4.1, at 75% relative humidity (Madampe & Puttalam areas have about 75% RH), the moisture absorption of Silica gel is about 33% of its original weight. However, there are few types of Silica gels. Blue colored is the one which is used in CEB Transformers. Therefore, it was required to verify the moisture absorption capacity given in 'An evaluation of Silica gel for humidity control in display cases'[24] by doing an experiment using blue colored Silica gel.

Accordingly, in order to find out the moisture absorption of Silica Gel used in Transformers; the experiment has been carried out. The experiment was repeated two times at 2 locations (One at Madampe GS and one at Puttalam GS) to get the better result. As Madampe & Puttalam areas have similar kind of environmental conditions, results of these experiments were expected to be same in all these three areas. According to the available past environmental data, Relative Humidity in Madampe & Puttalam areas are about 75% [20][21]. Therefore, experiments have been carried out under75% relative humidity-controlled condition. Following are only expectations of the experiments.

- To identify the Moisture absorption capacity of Silica gel used in CEB Transformers at Madampe and Puttalam areas. This is required to confirm whether the silica gel in the breathers of selected Transformers is getting saturated or not before replacing the silica gel.(Silica gel replacement is generally done once in 12 months)
- To get an idea on the moisture absorption rate. This is required to calculate the amount of moisture absorption per month.

4.3.1 Moisture absorption experiment at 75% Relative Humidity

'Saturated Salt Solutions and control of Air Humidity'[25] shows that, keeping saturated NaCl (salt) solution in sealed container makes it a 75% relative humidity condition. To become the particular volume of environment saturated, the amount of salt solution that need to be kept is available in [22]. That condition remains same from 20^0C to 40^0C. The average temperature at Madampe and Puttalam area is about 28 ^{0}C[21]. Then, the amount of salt solution required to be used for this experiment has been calculated as below.

Volume of the sealed box used for the experiment = Height * Width * Length

= 150mm * 280mm * 390mm

= 16,380,000 mm^3

= 0.01638 m^3

From [19][20][21], the average temperature in Bolawatta, Madmpe and Puttalam area is 28 ^{0}C.

From [22], the minimum amount of water saturated with salt required to be kept in $1m^3$ volume is 18g at temperatures from 20^0C to 40^0C.

Hence, the minimum amount of water saturated with salt required

to be kept in the box = Volume of sealed box * The amount of salt solution required to saturate $1m^3$ volume

$= 0.01638\ m^3 * 18\ g/m^3$

$= 0.29484\ g$

$= 0.3\ ml$

Hence, keeping more than 0.3ml of saturated salt solution inside the sealed selected box can produce 75% relative humidity. Similar setups have been used in other researches as well [26],[27].

Method used for the experiment is given below,

- 500g of NaCl has been put into 200ml of water containing cup and then mixed it so that it became a saturated NaCl solution. Saturated NaCl solution has been obtained by mixing NaCl with water until it is not dissolving further in the water, and there is un-dissolved NaCl on the bottom of the solution containing cup.
- Then that cup has been kept inside a sealed plastic box with 0.01638m3 volume for 2 days to become the inside of the box become 75% relative humidity.
- While keeping the NaCl solution inside the box, a digital scale was kept inside the box and then 100g of silica get containing tray has been kept on the scale. Silica gel has been spread on the tray so that the height of the layer becomes just a silica gel bead. Tray has been vibrated regularly to rotate each Silica gel bead to have maximum exposure to the air inside.
- After closing the box, Silicon has been applied around the cover to ensure the proper sealing. Since the relative humidity of environment in these area is also about 75% [19][20][21], even if the box is not perfectly sealed, there cannot be any leakage or humidity migration between inside and the outside of the box.
- Then, weight of the Silica gel has been measured regularly until the silica gel becomes fully saturated with moisture.
- Same experiment was conducted two times at Bolawatta GS, one time at Madampe Gs and one time at Puttalam GS parallel by using exactly same size of boxes, same volumes of water and same weights salt and silica gel.

Figure 4.2, shows the sealed plastic boxes which contain NaCl solution, Silica gel and electronic scale for repeated Madampe experiment and one Puttalam experiment respectively.

Figure 4.2 Experiment arrangement at 75% relative humidity [26],[27]

Results are shown in Figure 4.3 and explained below.

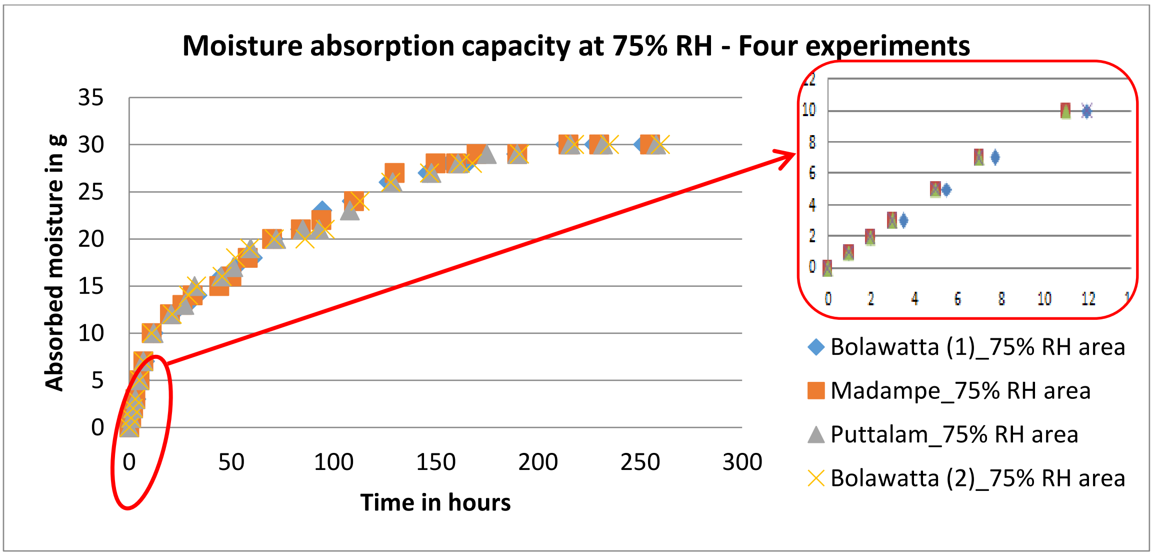


Figure 4.3 Moisture absorption at 75% relative humidity [26],[27]

Based on the experiment results, 100g of Silica gel has absorbed 30g of moisture before it got saturated at 75% relative humidity-controlled condition. Hence, it can be estimated that 30% of moisture can be absorbed by Silica gel before it gets fully saturated at Bolawatta, Madampe and Puttalam areas as these areas have about 75% relative humidity. Further, it is also clear that the moisture absorption rates up to about 10% absorption is linear and thereafter the rate get reduces and drying efficiency of Silica gel becomes less.

Table 4-2, shows the maximum estimated moisture absorption capacities of Silica gel breather in studied Transformers based on the above assumption and Silica gel quantity in the breather.

Table 4-2 Maximum estimated moisture absorption by breather for Transformers

Transformer	Rated weight of Silica gel in the breather (kg)	Maximum moisture absorption capacity (30% of Silica gel weight) (g)
Madampe Transformer 02	12	3,600
Puttalam Transformer 01	12	3,600
Puttalam Transformer 02	12	3.600

4.3.2 Experiment on Actual moisture absorbed by Breather in Madampe Transformer 02

As described in section 3.2.1 in method Chapter, another experiment has also been carried out in order to identify the actual amount of absorbed moisture by breather in Madampe Transformer 02. Last silica gel replacement of Breather in Madampe Transformer 2 has been done 16 months ago. Breather contained two cylindrical units as shown in Figure 4.4. Experiment has been carried out to estimate the actual moisture absorption rate by Silica gel breathers which in operation. Figure 4.4, shows the exact orientation of the Silica gel breathers installed in Madampe Transformers.

Figure 4.4 Breather at Madampe Transformer 02

Method used for the experiment is given below,

- Total quantity of moisture absorbed Silica gel in the two cylindrical breather units have been taken out and total weight has been measured immediately.
- Removed Silica gel has been heated to remove all the moisture in it.
- Immediately after the removing of moisture, weight has been measured.
- Then, from the weight difference of before and after heating the Silica gel, total amount of moisture that had been absorbed by the breather has been calculated.

Experiment, [26],[27] works such as removing Silica gel from breather, measuring the weight of Silica gel and heating the Silica gel to remove its moisture are respectively shown in Figure 4.5.

Figure 4.5 Experiment on breather at Madampe Transformer 02

Total absorbed moisture for 16 months has been calculated as bellow.

Total weight of removed moisture absorbed Silica gel	= 13,986 g
Total weight after removing its moisture by heating	= 12,978 g
Hence, total moisture absorbed by Silica gel for 16 months	= Weight before heating – Weight after heating
	= 13,986 – 12,978
	= 1,008 g
Moisture absorbed % for 16 months	=(Total moisture absorbed/ quantity of Silica gel in the breather) * 100
	= $(1{,}008/12{,}978) * 100$
	= 7.77%

According to the experiment, it has been calculated that the moisture absorption for 16 months is less than 8% of its Silica gel weight. Therefore, it was very clear that the Silica gel has not got saturated with moisture.

From Figure 4.3, rate of moisture absorption up to about 10% of Silica gel is linear. According to the experiment calculation, breather of Madampe Transformer 02 has not reached to 10% of absorbed moisture within 16 months. Hence, it has been assumed that the moisture absorption rate was constant and drying efficiency dynamics need not to be considered. As a practice, Silica gel is being replaced once in 12 months. Accordingly, the monthly amount of moisture absorption by Silica gel breather has been estimated as below.

Total moisture absorbed by 12kg sized Silica gel	
breather for 16 months	= 1,008 g
Hence, Moisture absorption per month (by 12kg sized breather)	= Total moisture absorbed / No.s of months
	= $1{,}008/16$
	= 63 g

Therefore, 12 kg sized Silica gel breather absorbs 63 g per month and 6 kg rated sized Silica gel breather absorbs 31.5g per month.

4.4 Calculation of Moisture Adding through Inhaling

As described in section 3.2.1 in method Chapter, moisture adding to the Transformers through inhaling have been calculated as shown below.

For the calculation, following assumptions have been made.

- Moisture absorption is equal per month and taken as 63g for 12kg sized Silica gel breathers and 31.5g for 6kg rated sized Silica gel breathers based on above estimations.
- Constant relative humidity was there throughout the month (Averaged RH%).

4.4.1 Amount of moisture ingress to the Transformer

Oil temperature data of these Transformers were not available from the date of commissioning of the Transformer. Therefore, 24-hour oil temperature readings have been taken for last 5 years and averaged values have been used for the whole calculation from the commissioning date till its end of life.

For each month, first week's 24-hour oil temperature readings have been taken and then averaged.

Figure 4.6, shows the 24-hour daily oil temperature variation of Madampe Transformer 02 for the month of January for last 5 years in operation.

Figure *4.7*, shows the averaged 24-hour daily oil temperature variation of Madampe Transformer 02 for the month of January. Averaged 24-hour oil temperature readings for one day are assumed to be same throughout the month.

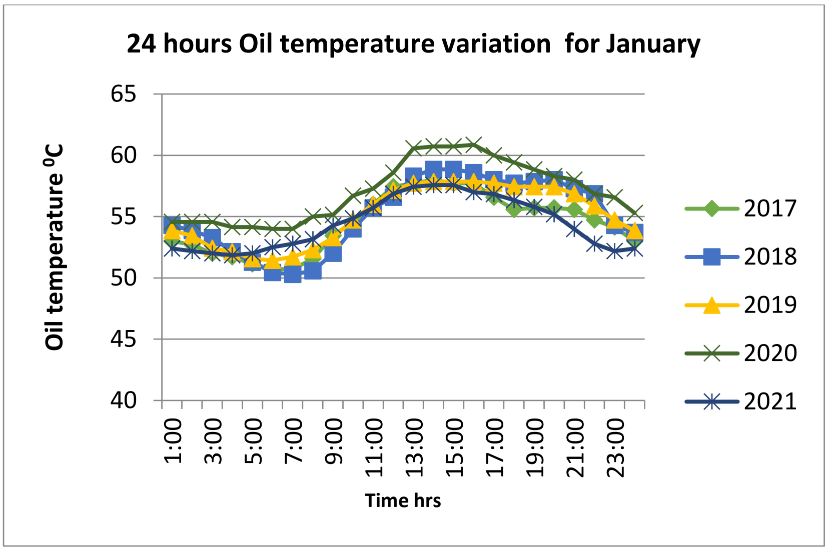


Figure 4.6 24-hour oil temperatures in January for Madampe TF02

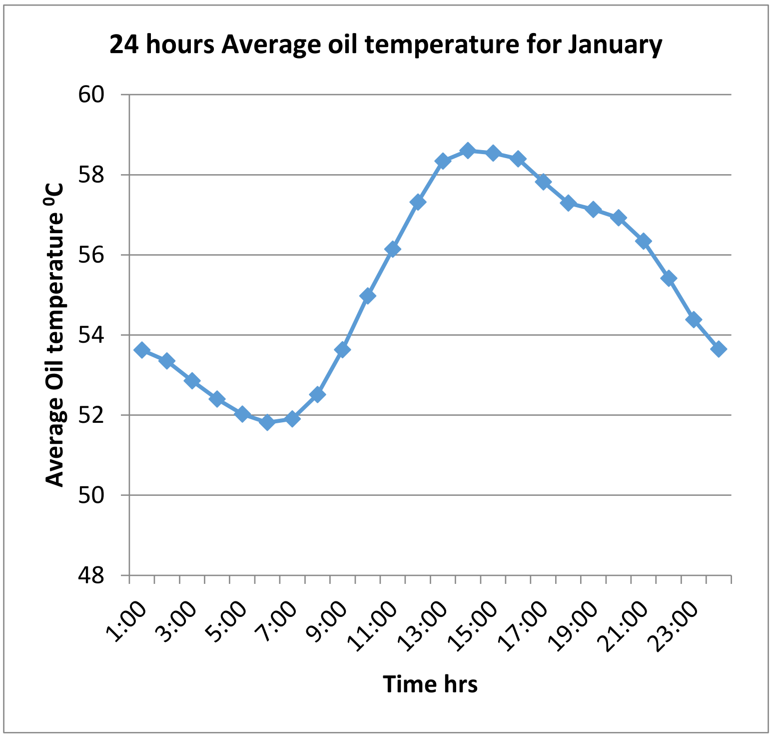


Figure 4.7 24 Hour average oil temperatures in January for Madampe TF02

Similar set of average oil temperature characteristics for all other eleven months have been estimated same way. Averaged oil temperatures of all 3 Transformers for all 12 months are in Appendix A. Average oil temperature variation per day for each month has been calculated by taking the difference between maximum oil temperature and minimum oil temperature.

Sample calculation for the month of January for Madampe Transformer 02 is illustrated below.

For January, average oil temperature variation per day =Maximum Temperature of the day – Minimum Temperature of the day

= 59 ^{0}C – 52 ^{0}C

= 7 ^{0}C

Thermal expansion coefficient for mineral oil is 7.5 X 10^{-4} $^0C^{-1}$ according to the 'Mineral Transformer oil' [18]

From Table 4-1, oil volume of the Madampe Transformer 02 is 18.54 m^3.

Therefore, oil volume change of Madampe Transformer 02 per day in January month has been calculated as below.

Oil volume change per day in January = Oil volume X Thermal expansion coefficient X Daily temperature variation

= 18.54 m^3 X 7.5 X 10-4 0C-1X 7 ^{0}C

= 0.097335 m^3

Same amount of atmospheric air is inhaled into the Transformer. Hence, 0.097335 m3 atmospheric air is inhaling into the Transformer per day.

Therefore, atmospheric air inhaling into the Madampe

Transformer 02 for the month of January =Volume of Atmospheric air inhaled per day X No days in the month

= 0.097335 m^3 X 31 days

= 3.017385 m^3

From ‘Chilaw Climate Weather Averages’ [19], Average relative humidity and average ambient temperature data on January month of 2021 for Madampe (Chilaw) area has been taken and values are as below.

Average Relative humidity is 74%. The calculation has been done under the limitation of assuming 74% relative humidity is available throughout the full span of operation time at Madampe area for January months.

Average day time ambient temperature is 31 ^{0}Cand average night time ambient temperature is 23 ^{0}C

Hence, Average ambient temperature =(Maximum temperature of the day + Minimum temperature of the day)/2

= (31 ^{0}C +23 ^{0}C)/2

= 27 ^{0}C

The calculation has been done under the limitation of assuming 27 ^{0}C average ambient temperature is available throughout the full span of operation time at Madampe area for January months.

From M. Jankovec et. al. [22], at particular temperature and relative humidity, the amount of moisture in the unity volume of ambient air has been estimated using Figure 3.2.

For Madampe Transformer 02, at 74% relative humidity and 27 ^{0}C average ambient temperature, the moisture in ambient air is 22 gm^{-3}.

Hence, amount of moisture inhaled into the Transformer

for the month of January = Volume of atmospheric air inhaled into the Transformer for the month X amount of moisture available in the unity volume of atmospheric air

= 3.017385 m^3 X 22 gm^{-3}

= 66.38247 g

Same calculation is performed for all 12 months and for all 3 Transformers based on the parameters relevant to them.

4.4.2 Amount of moisture remained in the Transformer

Sample calculation of Madampe Transformer 02 for January month for the remaining moisture calculation is shown below.

Based on above calculation and experiment on breather of Madmpe Transformer 02,

Moisture inhaled into the Transformer during January = 66.38247 g

Moisture absorbed by Silica gel breather per month = 63 g

Thus, moisture added into the Madampe Transformer 02

for the month of January through inhaling = Amount of moisture inhaled into the Transformer for the month – Amount of moisture removed by the breather for the month

= 66.38247 g - 63g

= 3.38247 g

Similar way, moisture added into the Transformer through inhaling has been calculated for all 12 months and for all 3 Transformers. Same pattern was assumed to be happening in every year.

Table 4-3 and Figure 4.8 show the calculated added moisture in Madampe Transformer 02 for 2015 through inhaling. Same calculation has been done for other three Transformers too by taking particular data relevant to those Transformers and are as ‘Puttalam climate weather averages’[20].

Table 4-3 Calculated added moisture in Madampe TF 2 for 2015

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Au g**	**Sep**	**Oct**	**Nov**	**Dec**
RS% at Madampe	74	73	75	77	79	82	82	82	81	80	79	79
Ambient temp. Day	31	32	32	32	31	30	29	29	29	30	31	30
Ambient temp. Night	23	24	25	26	27	26	26	25	25	25	25	24
Average ambient temp.	27	28	28.5	29	29	28	27.5	27	27	27.5	28	27
Moisture in air at atmosphere	22	22	22	23	23	22	22	22	22	22	22	22
Temp Variation	7	8	8	8	8	6	7	6	6	7	7	6
Volume Change	0.09	0.11	0.111	0.11	0.111	0.08	0.09	0.08	0.08	0.09	0.09	0.08
Moisture went inside	66.3	68.5	75.86	76.7	79.31	55	66.3	56	55	66.3	64.2	56
Moisture absorbed by breather	63	63	63	63	63	63	63	63	63	63	63	63
Dissolved moisture in TF	3.38	5.52	12.86	13.75	16.31	0	3.38	0	0	3.38	1.24	0

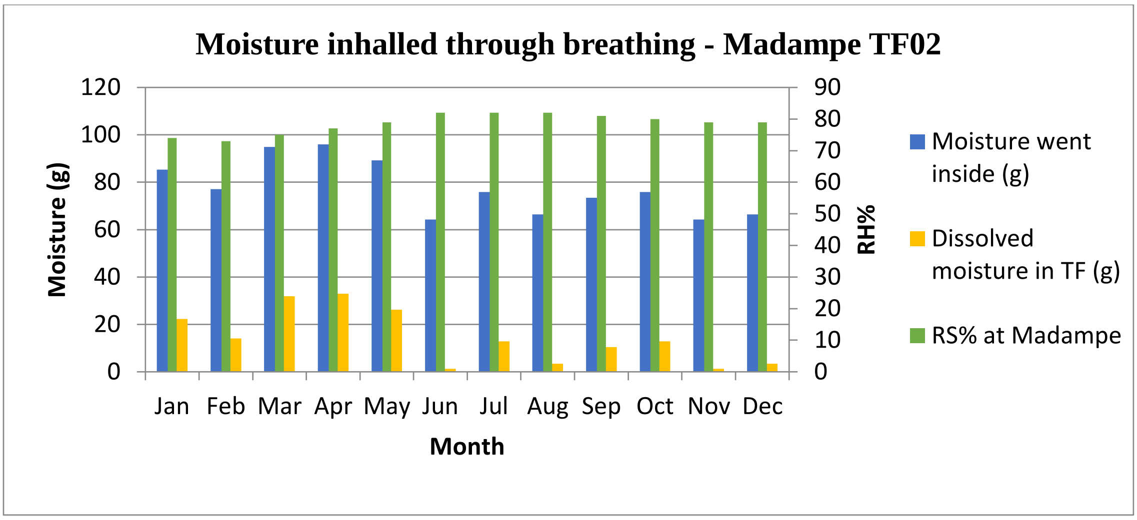


Figure 4.8 Calculated remained moisture amount through inhaling in Madampe Transformer 02 for 2015

4.5 Moisture Absorbed through Oil Leakages

As described in section 3.2.2 in Method Chapter, the moisture adding through oil leaks has been calculated as shown below.

Available recorded details of major oil leakages over the full period of time of Transformers in operation have been collected and tabulated as in Table 4-4. Details include No.s of oil leaks and duration of the oil leaks.

Table 4-4 Oil leakages details

Transformer	No.s of oil leakages	No.of months	Month and year
Madampe TF02	1	3	Feb-2010, Mar-2010, Apr-2010.
	2	3	May-2010, June-2010, July-2010.
	1	4	Feb-2020, Mar-2020, Apr-2020, May-2020
	2	2	Jun-2020, Jul-2020.
	4	2	Aug-2020, Sep-2020.

As described in Table 2-1 in the Chapter 02, moisture adding into the Transformer per oil leak per month has been calculated as below.

According to the collected data, all the oil leaks of studied Transformers are viscous flow due to insufficient sealing. Therefore, Moisture adding per oil leak is 15g per day from Table 2-1.

Hence,

$$Total\ moisture\ adding\ due\ to\ oil\ leaks\ of\ Transformer\ per\ month$$
$$= No.of\ oil\ leaks * No.of\ days\ in\ the\ month * 15g$$

Therefore, the total amount of moisture added in to the Madampe Transformer 2 for the month of June 2020 has been calculated as below,

$$Total\ moisture\ adding\ due\ to\ oil\ leaks\ of\ Transformer$$
$$= No.of\ oil\ leaks * No.of\ days\ in\ the\ month * 15g$$

= 2 * 30 * 15g

= 900g

Similar way moisture adding due to the oil leakages of a particular Transformer has been calculated monthly throughout the period that oil leakages exist.

4.6 Moisture Adding through Ageing of Paper

Another important source of moisture is ageing itself. Ageing of the paper insulation produces the water. Water produces by ageing of paper insulation is directly related to the degree of polymerization. At higher DP values, less amount of water is produced and when the DP value becomes low, higher amount of water is produced.

As described in section 3.2.3 in Method Chapter, the moisture adding through paper ageing has been calculated as shown below by using different sets of equations at above 350 DP values and below 350 DP values.

According to the Figure 2.7, prepared from various researchers' results show the moisture content produced through ageing with reference to the chain scission. Data points of those results have been taken into the Figure 4.9.

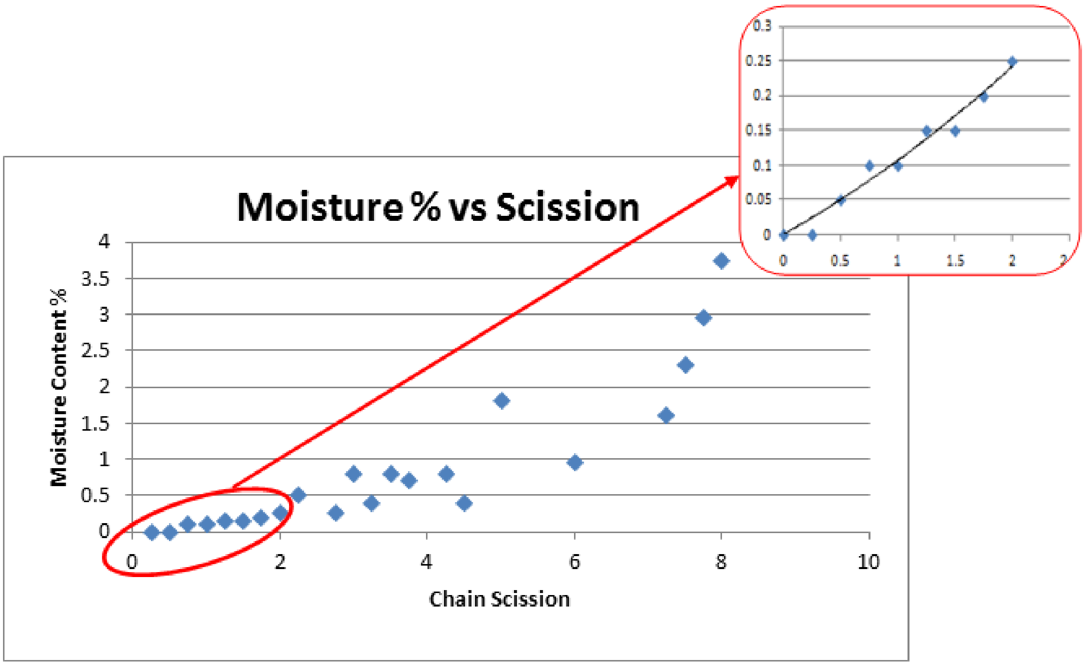


Figure 4.9 Relation between moisture content and chain scission [26]

Moisture content gradually increases with the chain scission. From the Figure 4.9, up to 2 chain scissions, data points are more stable and it shows smoothly increasing characteristics of moisture content against the chain scission. Hence, up to 2 chain scissions, this data has been used for the calculation. Up to 2 chain scissions, data points have been filtered in to Figure 4.10.

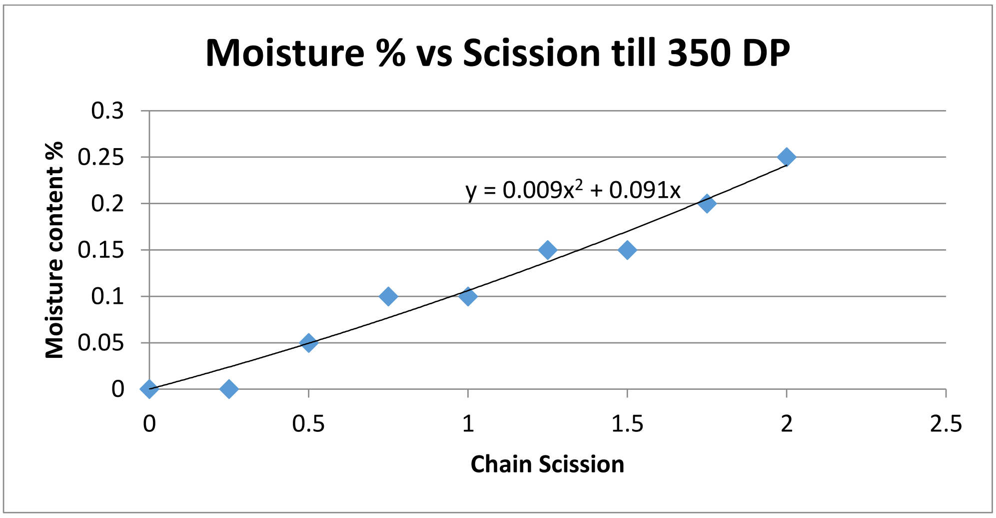


Figure 4.10 Relation between moisture content and chain scission up to 2

From the Figure 4.10, following equation has been derived.

$$Y = 0.009x^2 + 0.091x \qquad (4\text{-}1)$$

Where, x is chain scission and Y is moisture content.

From [5],

$$DP = \frac{1000}{(1 + Chain\ Scission)} \qquad (4\text{-}2)$$

Based on ((*4-1*) and ((*4-2*), Figure 4.11 was prepared where moisture content is shown with reference to the DP value.

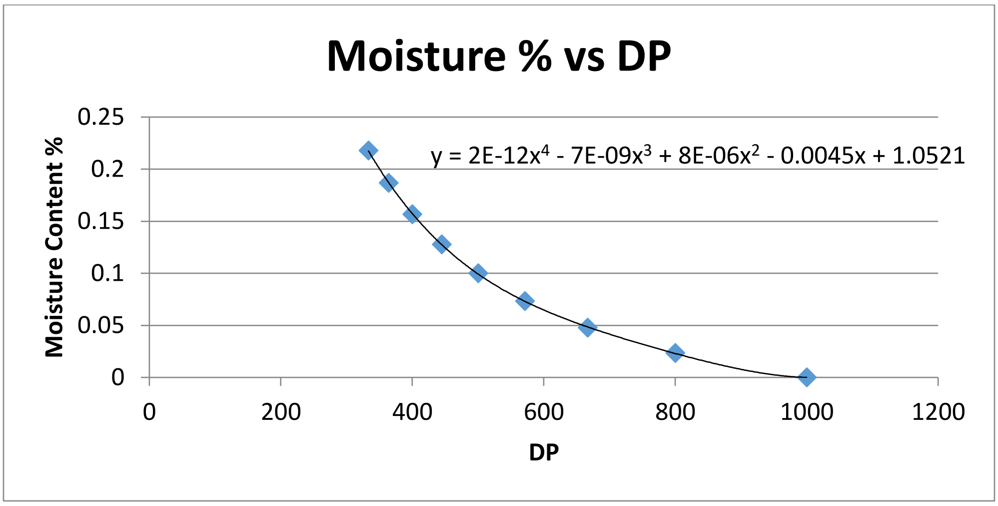


Figure 4.11 Relation between moisture content and DP

From the Figure 4.11, following equation has been derived.

$$Y = (2 * 10^{-12})x^4 - (7 * 10^{-9})x^3 + (8 * 10^{-6})x^2 - 0.0045x + 1.0521 \qquad (4\text{-}3)$$

Where, x is DP and Y is moisture content

Moisture content multiplying by paper weight of particular Transformer, the amount of moisture can be calculated.

Accordingly, the amount of moisture produced through ageing of paper with reference to the DP value has been calculated for Madampe Transformers and results are shown in Figure 4.12.

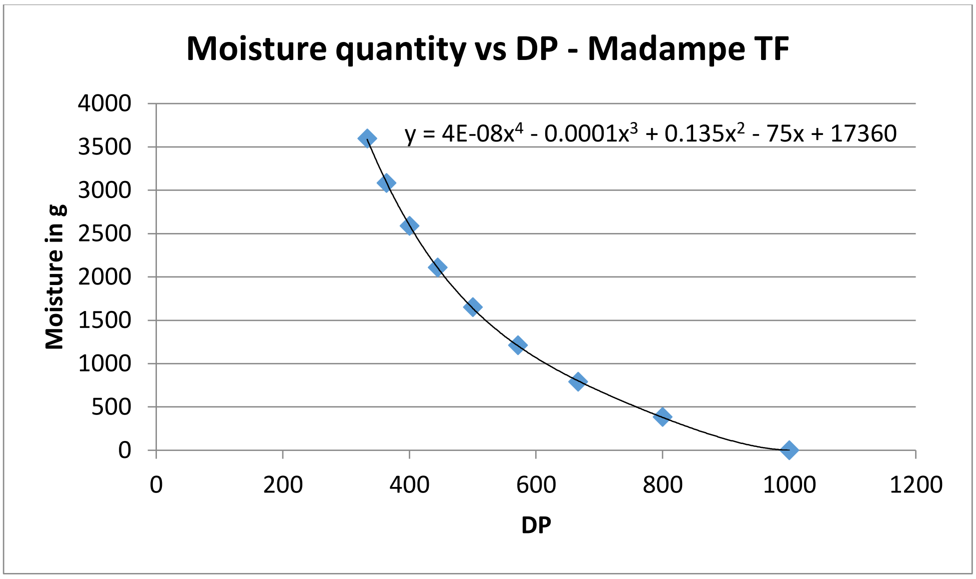


Figure 4.12 Moisture variation of Madampe Transformers with DP

From Figure 4.12, following equation has been derived for Madampe Transformers.

$$Y = (4 * 10^{-8})x^4 - (0.0001)x^3 + (0.135)x^2 - 75x + 17360 \quad (4\text{-}4)$$

Where, Y is moisture produced from ageing and x is DP value

Similar way equation (4-5 for Puttalam Transformers

$$Y = (3 * 10^{-8})x^4 - (0.0001)x^3 + (0.125)x^2 - 69.54x + 16098 \quad (4\text{-}5)$$

In order to estimate the moisture produced from ageing, equation ((4-3), ((4-4), and ((4-5) have been used for further moisture calculations at DP values of higher than 350.

Further, more accurate data regarding the moisture generates from ageing at lower DP values were presented by J Fabreet. al.[4] in Figure 4.13 and by Lungard et. al.[1]in Figure 4.14 as shown below.

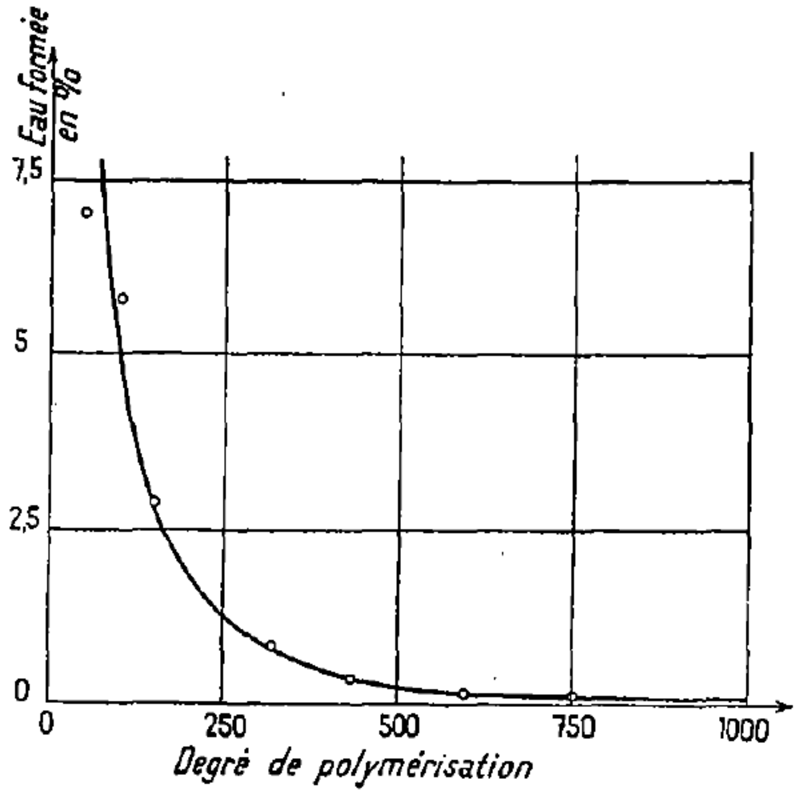


Figure 4.13 Relation between moisture content and DP [4]

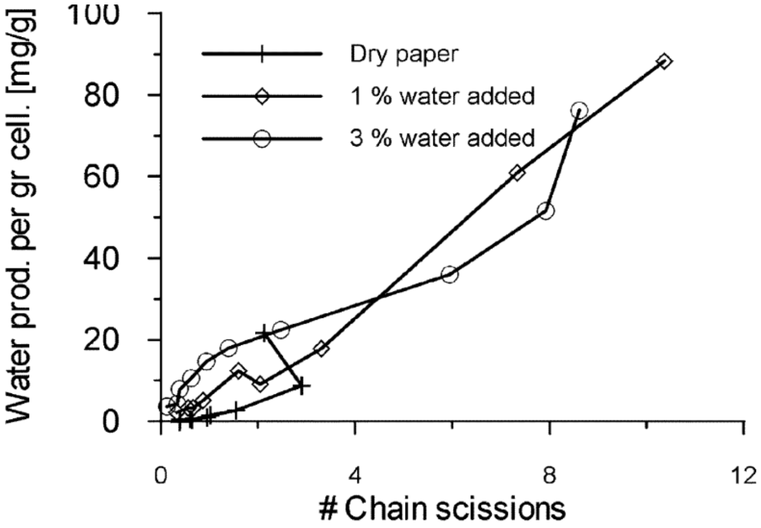


Figure 4.14 Relation between water and chain scission [1]

As Figure 4.14 has been prepared considering the initial DP is 1200, it has been equalized to initial DP of 1000 as below in order to combine both the data in Figure 4.13 and Figure 4.14.

$$DP(1200) = \frac{1200}{(1 + Chain\ Scission)} \quad (4\text{-}6)$$

$$DP(1000) = DP(1200)\frac{1000}{1200} \quad (4\text{-}7)$$

Where, DP(1200) is DP value considering initial DP as 1200 and DP(1000) is DP value considering initial DP as 1000.

From Figure 4.14 and using ((4-6) and ((4-7), Table 4-5 has been prepared.

Table 4-5 Equalized Moisture content values for 1000 DP

Chain Scission	M%	DP (1200)	DP(1000)
1.5	1.2	480	400
2	0.8	400	333.3333

3.33	1.8	277.13626	230.9469
7.33	6.2	144.05762	120.048

Data of the Figure 4.13 was included to Table 4-5 and Table 4-6 has been prepared combining both the data.

Table 4-6 Moisture at different DP values

DP(1000)	M%	Moisture in g
107.1428571	5.77	53949.5
120.048	6.2	57970
151.7857143	2.95	27582.5
230.9469	1.8	16830
321.4285714	0.83	7760.5
333.333	0.8	7480
400	1.2	11220
428.5714286	0.37	3459.5

Figure 4.15, illustrates the moisture content with reference to DP value data in Table 4-6.

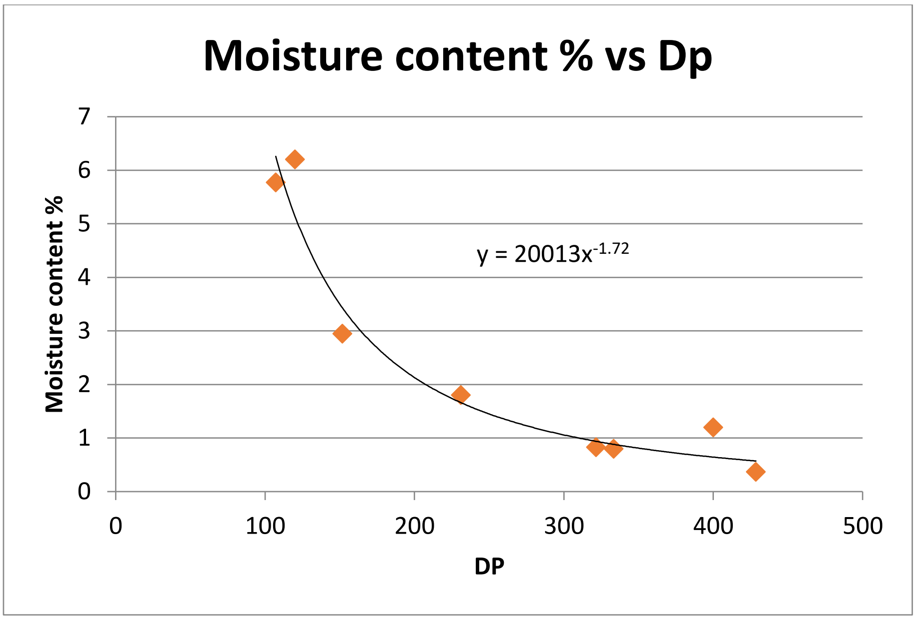


Figure 4.15 Relation between Summarized moisture content and DP

From Figure 4.15, ((4-8) has been derived as below.

$$Y = 20013x^{-1.72} \qquad (4\text{-}8)$$

Where, Y is moisture content generates by ageing and x is DP value

Moisture content multiplying by paper weight of particular Transformer, Amount of moisture can be taken.

Hence, Moisture amount generates by ageing with reference to DP value was calculated from equation (4-8 and Figure 4.16 has been prepared for Madampe Transformer 02.

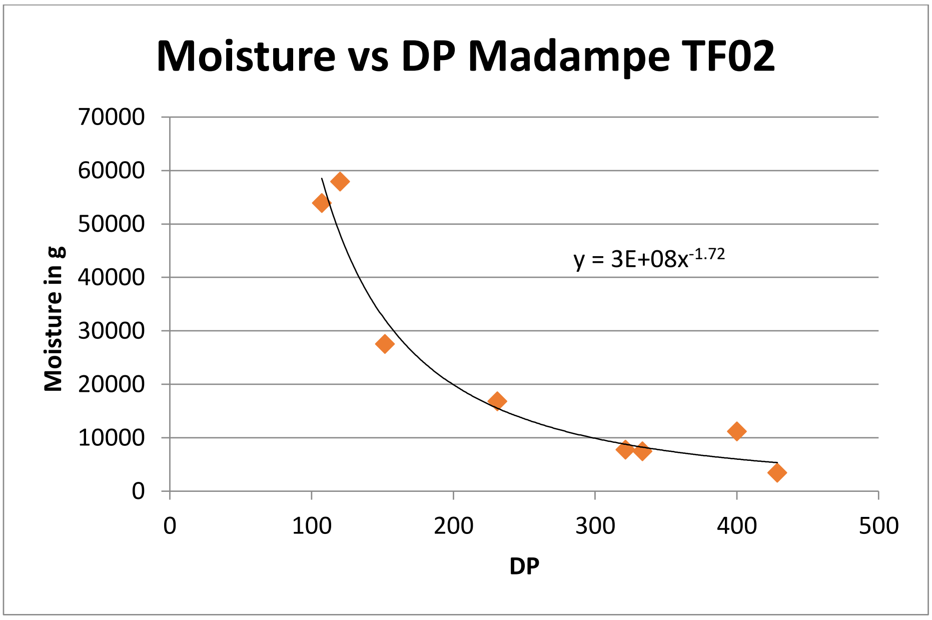


Figure 4.16 Relation between Moisture content and DP of Madampe Transformer 02

From Figure 4.16, equation(4-9has been derived as below.

$$Y = 3.3 * 10^8 x^{-1.72} \qquad (4\text{-}9)$$

Similar way, equation (4-10 for Puttalam Transformers have been derived.

$$Y = 3 * 10^8 x^{-1.72} \qquad (4\text{-}10)$$

Where, Y is amount of moisture generates by ageing and x is DP value

For further moisture calculations, equations ((4-9), ((4-10) have been used to calculate the moisture generates from ageing at DP values of less than 350.

4.7 Moisture removed through oil filtering

As described in section 3.2.4 in Method Chapter, the moisture removing through offline and online oil filtering have been calculated as shown below.

Oil filtering of Transformers is carried out on regular basis to remove some amount of moisture in the Transformer. There are two types of oil filtering are carried out as listed below.

- Offline oil filtering
- Online oil filtering

4.7.1 Offline oil filtering

As the name implies, offline oil filtering is carried out after de-energizing the Transformer. In order get the water out from paper insulation, circulating oil will be heated using heaters in the filter plant while filtering.

Amount of moisture removing from offline oil filtering is calculated as shown below,

14-day offline oil filtering has been carried out on removed Transformer 01 at Bolawatta GS on 2019 to remove its moisture and to uphold its condition as a special maintenance work. Maintenance report is attached as Appendix B. According to the maintenance report, the amount of moisture removing by offline oil filtering per day has been calculated as below.

Oil weight of the Bolawatta removed Transformer 01 is 9350kg.

Therefore, paper weight = 10% X oil weight

= 10% X 9350 kg

= 935,000 g

Moisture content before oil filtering = 2.85%

Thus, amount of moisture in TF before filtering = Moisture content before filtering X Oil weight of the Transformer

= 2.85% X 935,000 g

=26,647.5 g

Moisture content after oil filtering of 14 days = 2.2%

Thus, amount of moisture in TF after filtering = Moisture content after filtering X Oil weight of the Transformer

= 2.2% X 935,000g

=20,570 g

Hence, removed amount of moisture for 14 days = Amount of moisture before filtering – Amount of moisture after filtering

= 26,647.5 g - 20,570 g

= 6,077.5 g

Thus, removed moisture per day by offline oil filtering = Total amount of moisture removed / No.s of days

= 6,077.5 g / 14 days

= 434 g

For further moisture calculations, moisture removing from offline oil filtering per day has been considered as 434 g.

4.7.2 Online oil filtering

As the name implies, online oil filtering is carried out while the Transformer is in operation. Due to the load of the Transformer, oil is heated up to some extent and as a result moisture in the paper is coming out. However, online oil filtering is not as effective as offline oil filtering.

The Table 4-7, shows the oil filtering details of studied Transformers. Details include type of filtering and the duration of filtering.

Table 4-7 Oil filtering data of Transformers

	Offline filtering		**Online filtering**	
Transformer	**No. of oil filtering days**	**Month and year**	**No. of oil filtering days**	**Month and year**
Madampe TF01	3	May-2015.	-	-
Madampe TF02	3	July-2010.	-	-
	3	Sep-2020.	-	-
Puttalam TF01	3	Jul-2016.	-	-

Puttalam TF02	3	May-2016.	-	-

4.8 Dynamic Calculation of Moisture Content %

As discussed above, considering the moisture content has been calculated at the end of each month. Following methodology has been used to calculate the moisture content of a particular Transformer.

Considering all moisture adding and removing methods discussed above, the total amount of moisture added into the Transformer for particular month has been calculated as below using ((3-5),

$$\begin{aligned}
&Moisture\ added\ in\ to\ the\ Transformer\ for\ the\ month \\
&= (Remained\ moisture\ inhaled\ through\ breathing \\
&+ Moisture\ generated\ through\ ageing \\
&+ Moisture\ came\ from\ oil\ leakages) \\
&- (Moisture\ removed\ through\ offline\ oil\ filtering \\
&+ Moisture\ rmoved\ through\ online\ oil\ filtering)
\end{aligned}$$

Moisture which is already available in the Transformer is calculated based on the last month's moisture content and by adding it to the above added amount, the total amount of moisture that is present in the month has been calculated as below using ((3-6),

$$\begin{aligned}
&Moisture\ amount\ for\ the\ month \\
&= (Moisture\ content\ of\ previous\ month \\
&* Paper\ weight\ of\ the\ Transformer) \\
&+ Moisture\ remained\ in\ the\ Transformer\ for\ the\ current\ month
\end{aligned}$$

Then, the moisture content for the month is calculated on monthly basis as below using ((3-7),

$$Moisture\ content\ at\ end\ of\ the\ month = \frac{Moisture\ amount\ for\ the\ month}{Paper\ weight\ of\ TF} * 100$$

Based on equations ((3-5), ((3-6) & ((3-7), moisture content of each and every month have been calculated as described in the flow chart of Figure 3.3 in Method Chapter. Calculated results of Madampe Transformer 02 for year 2010 are shown in

Table *4-8*.

Table 4-8 Calculated moisture content of Madampe Transformer 02 for 2010

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Remained Inhaled moisture (g)	3.38	5.52	12.87	13.76	16.31	0.00	3.38	0.00	0.00	3.38	1.24	0.00
Moisture from ageing (g)	12.82	12.89	17.02	16.90	17.75	13.53	19.10	15.65	12.59	14.20	14.04	15.00
Moisture due to oil leaks (g)		420	465	450	930	900	930					
Moisture removed from Offline Filtering (g)							1302					
Moisture removed from Online Filtering (g)												
Hence Moisture % in paper	0.69	0.70	0.72	0.75	0.78	0.84	0.89	0.87	0.87	0.88	0.88	0.88

According to the results in , moisture content has increased from 0.69 to 0.88 in the year 2010.

4.9 Assessment of Oxygen content of Transformers

As shown in Figure 3-1 in Method Chapter, Pre exponential factor ('A') depends on moisture content and the Oxygen level of the Transformer. Hence, 2nd required parameter for the calculation of 'A' is estimation of Oxygen level.

Oxygen levels have been defined as tabulated in Table 3-1 Definition of Oxygen levels, by N. Lelekakis et. al.[7] for the studies considering the easy evaluations. Same Oxygen level definition has been used for this study as well.

All the Transformers are free breathing Transformers. Hence, it is expected that all of them have high oxygen content.

4.9.1 Oxygen content measurement

Oxygen content of all the Transformers have been measured by analyzing the oil. Dissolve Gas Analysis (DGA) test kit of Morgan Shaffer brand has been used for the analyzing the oil. Test procedure is illustrated below.

- Oil sample collecting syringe has been cleaned with Transformer oil itself twice.
- Then, 100ml of Oil Sample has been collected into a syringe from bottom oil sample valves of Transformers so that no air bubbles go inside the syringe.
- Then the syringe has been inserted to the test kit and DGA results have been taken.
- DGA test reports of Madmape TF01 is in Figure 4.17 and its Oxygen amount is about 29000ppm which is greater than the Oxygen high threshold.

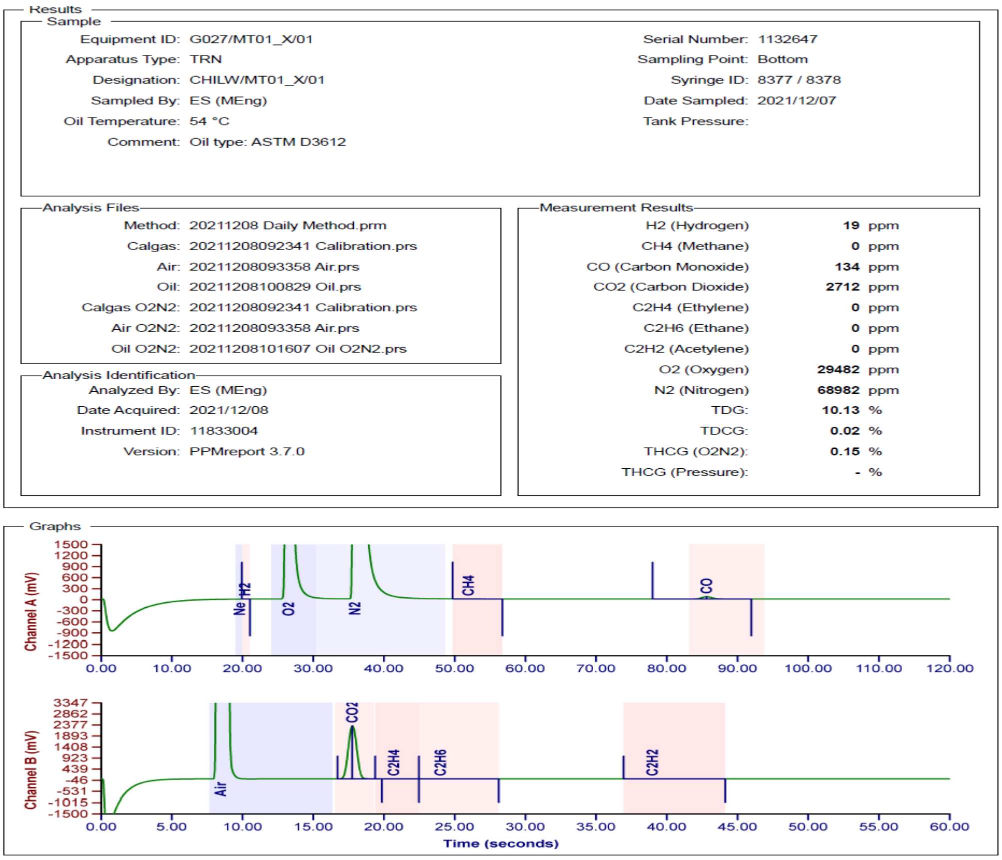


Figure 4.17 DGA report of Madampe Transformer 01

Only two samples from Madampe TF01 and Madampe TF02 have been taken for DGA and it has been found that Oxygen concentrations were respectively 29,482ppm and 30,697ppmas tabulated in Table 4-9. It was expected that both these Transformers have high Oxygen levels as both of them are free breathing Transformers. As expected, both the results were above Oxygen high threshold limit.

Table 4-9 DGA test results

Transformer	Oxygen Content (ppm)	Oxygen Level (Low/Medium/High)
Madampe TF01	29,482	High
Madampe TF02	30,697	High

Since all the Transformers are free breathing Transformers, it was assumed that all the Transformers have high Oxygen level.

However, oil filtering (which is along with oil degassing)is done time to time on these Transformers, followings were assumed,

- Transformer is assumed to be at low Oxygen level during the period from the day of oil filtering till Transformer inhaled ambient air equal to half volume of oil volume.
- Transformer is assumed to be at medium Oxygen level during the period from the Transformer inhaled ambient air equal to half volume of oil volume till full volume of oil volume.
- Transformer is assumed to be at high Oxygen level once the Transformer inhaled ambient air equal to full volume of oil volume and above.

Based on above assumptions, Oxygen levels of Transformers have been decided on monthly basis from the date of Transformer energization till its end of life.

4.10 Calculation of Pre exponential factor (A)

4.10.1 Calculation of multiplication factors for pre-exponential factor A

As described in Chapter 02, Table 2-2 represents the characteristics of pre exponential factor A with reference to the moisture content in paper insulation and Table 2-3 represents the characteristics of pre exponential factor A with reference to the Oxygen level in Transformer.

Then, the Multiplication factors for different Oxygen levels have been calculated as described in Table 3-2 in section 3.4 of Method Chapter.

4.10.2 Multiplication Factors of A for Moisture at Low Oxygen level (O2< 7000ppm)

From Table 2-2, Multiplication Factors (MFm) of A vs the Absorbed moisture at low oxygen level has been calculated as below.

From equation ((3-8),

$$Absorbed\ Moisture\ Content$$
$$= Moisture\ content\ of\ paper - 0.5$$

$$MFm\ for\ 0\%\ Absorbed\ moisture\ content$$
$$= 1$$

From equation ((3-9),

$$MFm\ for\ 0.5\%\ Absorbed\ moisture\ content = \frac{\text{A at 0.5\% absorbed moisture}}{\text{A at 0\% absorbed moisture}}$$

$$MFm\ for\ 0.5\%\ Absorbed\ moisture\ content = \frac{3.5 * 10^{08}}{1.4425 * 10^{08}}$$

$$MFm\ for\ 0.5\%\ Absorbed\ moisture\ content = 2.43$$

From equation ((3-9),

$$MFm\ for\ 1.1\%\ Absorbed\ moisture\ content = \frac{\text{A at 1.1\% absorbed moisture}}{\text{A at 0\% absorbed moisture}}$$

$$MFm\ for\ 1.1\%\ Absorbed\ moisture\ content = \frac{6.8 * 10^{08}}{1.4425 * 10^{08}}$$

$$MFm\ for\ 1.1\%\ Absorbed\ moisture\ content = 4.71$$

Similar way Multiplication Factor for absorbed moisture content of 1.5, 2.2, 3 and 3.5 at low oxygen level have been calculated and tabulated in Table 4-10.

Table 4-10 Multiplication factors for different moisture contents at low O_2 level

Moisture content %	$A_{average}$ /10^{08}	Absorbed Moisture content %	Multiplication Factor
0.5	1.4425	0	1.00
1	3.5	0.5	2.43
1.6	6.8	1.1	4.71
2	7.8	1.5	5.41
2.7	18.75	2.2	13.00
4	35	3.5	24.26

Table 4-10 has been taken in to the Figure 4.18 and it shows the variation of Multiplication factor of A at different Moisture contents and low oxygen level.

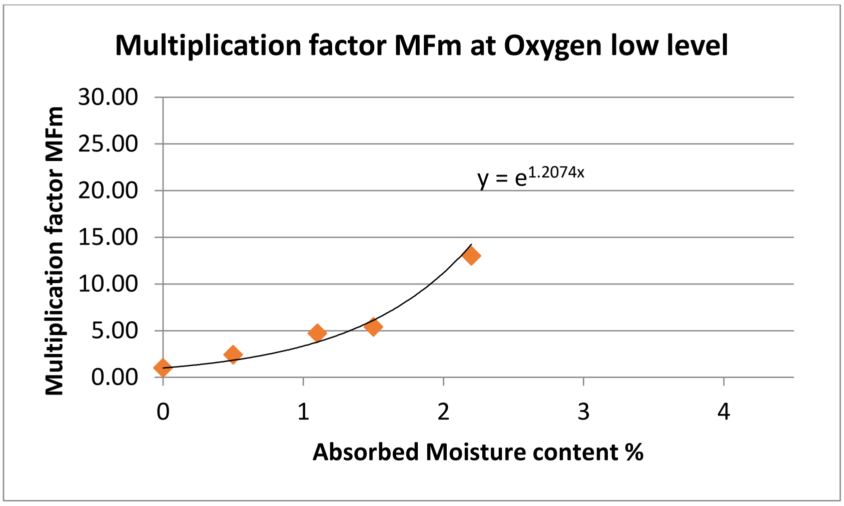


Figure 4.18 Multiplication factor variation at low O_2 level

Since moisture is generated by paper ageing itself, moisture increment in the Transformer is a chain reaction. Hence, moisture dependency of A should be an exponential equation. Accordingly, equation ((4-11) for the multiplication factor has been derived from Figure 4.18 as below.

$$Y = e^{1.2074x} \qquad \textit{(4-11)}$$

Where Y is Multiplication Factor MFm and x is absorbed moisture

4.10.3 Multiplication Factors of A for Moisture at medium oxygen level (7000ppm < O2< 14000ppm) (MFom)

From Table 2-3, MFom has been calculated so that A at medium oxygen level can be calculated by multiplying A at low oxygen level by MFom at same particular moisture content. Hence, actual A value to be taken by multiplying by both MFm and MFom. Calculation is as below.

From equation ((3-10),

$$MFom\ for\ 0\%\ absorbed\ moisture\ content$$
$$= \frac{A\ at\ 0\%\ absorbed\ moisture\ and\ medium\ oxygen\ level}{A\ at\ 0\%\ absorbed\ moisture\ and\ low\ oxygen\ level}$$

$$MFom\ for\ 0\%\ absorbed\ moisture\ content = \frac{9,.26 * 10^{08}}{1.28 * 10^{08}}$$

$$MFom\ for\ 0\%\ absorbed\ moisture\ content = 7.23$$

From equation ((3-10),

- $MFom\ for\ 1.1\%\ absorbed\ moisture\ content = 16$

$$MFom\ for 1.1\%\ absorbed\ moisture\ content = \frac{21.9 * 10^{08}}{8.25 * 10^{08}}$$

$$MFom\ for\ 1.1\%\ absorbed\ moisture\ content = 2.65$$

From equation ((3-10),

- $MFom\ for\ 2.2\%\ absorbed\ moisture\ content = \frac{A\ at\ 2.2\%\ absorbed\ moisture\ and\ medium\ oxygen\ level}{A\ at\ 2.2\%\ absorbed\ moisture\ and\ low\ oxygen\ level}$

$$MFom\ for\ 2.2\%\ absorbed\ moisture\ content = \frac{52 * 10^{08}}{30 * 10^{08}}$$

$$MFom\ for\ 2.2\%\ absorbed\ moisture\ content = 1.73$$

Results are tabulated in Table 4-11 and taken in to Figure 4.19.

Table 4-11 Multiplication factors for different moisture contents at medium O_2 level

Moisture content%	**Absorbed moisture content %**	**A /10^{08}**	**Multiplication Factor (medium oxygen)**
0.5	0	1.28	
1.6	1.1	8.25	
2.7	2.2	30	At low O_2 level
0.5	0	9.26	7.23
1.6	1.1	21.9	2.65
2.7	2.2	52	1.73

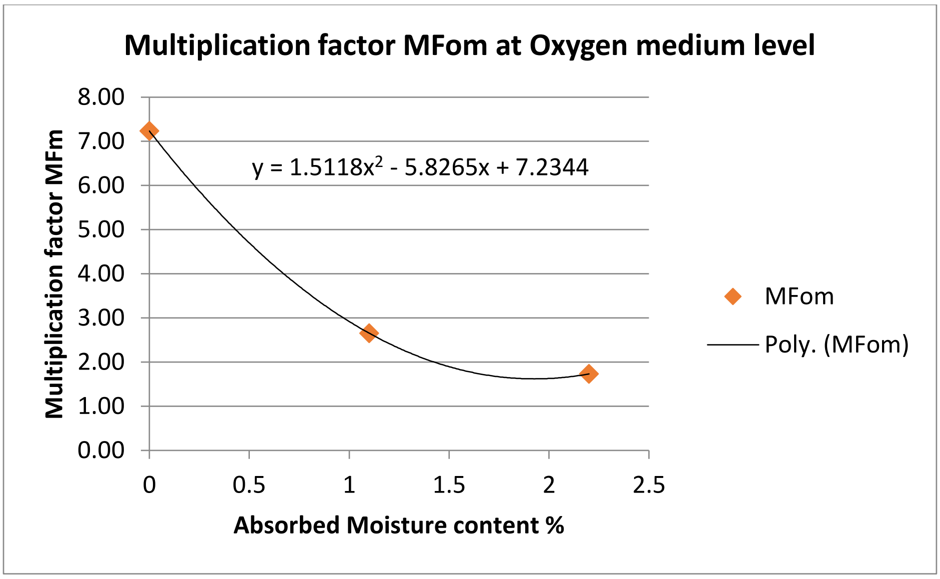


Figure 4.19 Multiplication factor variation at medium O_2 level

From Figure 4.19, an equation for the multiplication factor has been derived as

$$Y = 1.5118x^2 - 5.8265x + 7.2344 \qquad (4\text{-}12)$$

Where Y is Multiplication Factor MFom and x is absorbed moisture

4.10.4 Multiplication Factors of A for Moisture at high oxygen level (14000ppm < O2) (MFoh)

From Table 2-3, MFoh has been calculated so that A at high oxygen level can be calculated by multiplying A at low oxygen level by MFoh at same particular moisture content. Hence, actual A value to be taken by multiplying by both MFm and MFoh. Calculation is as below.

From ((3-11),

- $MFoh\ for\ 0\%\ absorbed\ moisture\ content = \frac{A\ at\ 0\%\ absorbed\ moisture\ and\ high\ oxygen\ level}{A\ at\ 0\%\ absorbed\ moisture\ and\ low\ oxygen\ level}$

$$MFoh\ for\ 0\%\ absorbed\ moisture\ content = \frac{17.34 * 10^{08}}{1.28 * 10^{08}}$$

$$MFoh\ for\ 0\%\ absorbed\ moisture\ content = 13.59$$

From equation (3-11,

- $MFoh\ for\ 1.1\%\ absorbed\ moisture\ content = \frac{A\ at\ 1.1\%\ absorbed\ moisture\ and\ high\ oxygen\ level}{A\ at\ 1.1\%\ absorbed\ moisture\ and\ low\ oxygen\ level}$

$$MFoh\ for\ 1.1\%\ absorbed\ moisture\ content = \frac{44.4 * 10^{08}}{8.25 * 10^{08}}$$

$$MFoh\ for\ 1.1\%\ absorbed\ moisture\ content = 5.38$$

From equation (3-11,

- $MFoh\ for\ 2.2\%\ absorbed\ moisture\ content = \frac{A\ at\ 2.2\%\ absorbed\ moisture\ and\ high\ oxygen\ level}{A\ at\ 2.2\%\ absorbed\ moisture\ and\ low\ oxygen\ level}$

$$MFoh\ for\ 2.2\%\ absorbed\ moisture\ content = \frac{74.1 * 10^{08}}{30 * 10^{08}}$$

$$MFoh\ for\ 2.2\%\ absorbed\ moisture\ content = 2.47$$

Results are tabulated in Table 4-12 and taken in to Figure 4.20.

Table 4-12 Multiplication factors for different moisture contents at high O_2 level

Moisture content%	**Absorbed moisture content %**	**A /10^{08}**	**Multiplication Factor (high oxygen)**
0.5	0	1.28	
1.6	1.1	8.25	
2.7	2.2	30	At low O_2 level
0.5	0	17.4	13.59
1.6	1.1	44.4	5.38
2.7	2.2	74.1	2.47

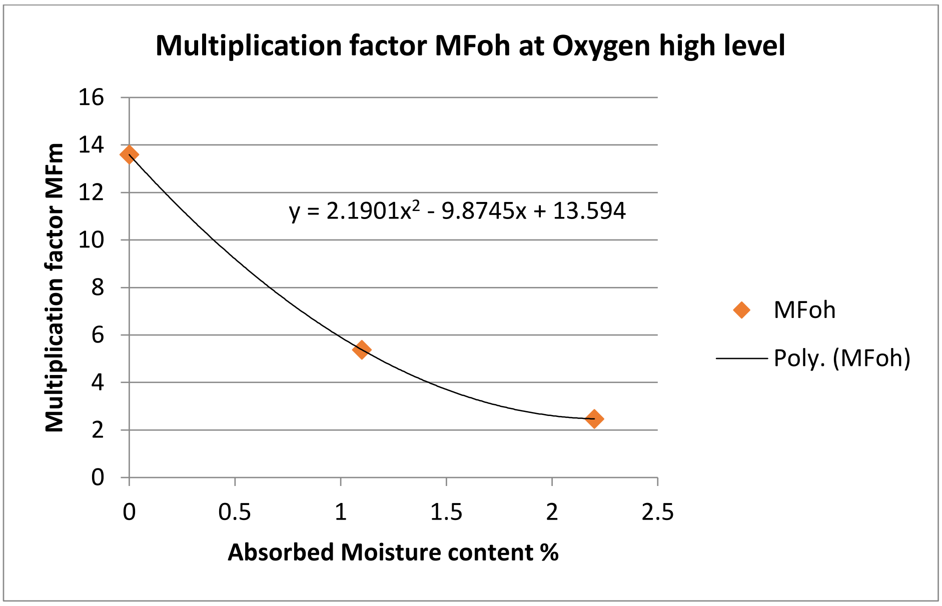


Figure 4.20 Multiplication Factor variation at high O_2 level

From Figure 4.20, an equation for the multiplication factor has been derived as

$$Y = 2.1901x^2 - 9.8745x + 13.594 \quad (4\text{-}13)$$

Where Y is Multiplication Factor MFoh and x is absorbed moisture

Based on ((4-11), ((4-12) and ((4-13), value of A can be corrected (A_{actual}) at different moisture levels and oxygen levels as below.

$$\text{A actual at low oxygen level} = \text{A at 0.5\% moisture content} * e^{-1.2074x} \quad (4\text{-}14)$$

$$A \text{ actual at medium oxygen level} = A \text{ at } 0.5\% \text{ moisture content} * e^{-1.2074x} * (1.5118x^2 - 5.8265x + 7.2344) \quad (4\text{-}15)$$

$$A \text{ actual at high oxygen level} = A \text{ at } 0.5\% \text{ moisture content} * e^{-1.2074x} * (2.1901x^2 - 9.8745x + 13.594) \quad (4\text{-}16)$$

Where x is absorbed moisture %.

At low Oxygen level and for dry paper (0.5% of moisture content),and the value of A is given as 1.28 X 10^{08} h^{-1} by the Nick lelekakiset. al.[7].

Then by using the equations (4-14, (4-15 and (4-16, value of A has been calculated at different moisture content and different oxygen levels as described below.

$A_{calculated}$ at low oxygen level = 1.28 X 10^{08} h^{-1} X equation (4-11

$A_{calculated}$ at medium oxygen level = 1.28 X 10^{08} h^{-1} X equation (4-11X equation (4-12

$A_{calculated}$ at high oxygen level = 1.28 X 10^{08} h^{-1} X equation (4-11X equation (4-13

As the moisture content and Oxygen levels have been calculated monthly, A has also been calculated monthly from the date of energization of the Transformer.

4.11 Calculation of Ageing rate (k)

According to the equation (*2-2*, k is temperature dependent. Therefore, temperature data have to be used to calculate the Ageing rate. As per the ((*2-2*, k depends on hot spot temperature.

4.11.1 Identification of Hot Spot Temperatures of Transformers

Transformer contains three temperature gauges which show three temperature readings as below.

1. Oil temperature
2. Primary Winding Temperature
3. Secondary Winding Temperature

The highest temperature is shown in Secondary Winding (LV) Temperature gauge. Some gauges are designed so that they give the average winding temperature whereas some are designed so that they give directly the Hot Spot temperature. In Madampe and Puttalam Transformers, which were taken for the study, indicated that it shows the Hot Spot temperature.

4.11.2 Temperature data collection

Hot spot temperature data of these Transformers were not available from the date of commissioning of the Transformer. These data are available only on the last 5 years of operation time. Therefore, 24-hour secondary winding temperature readings have been taken for last 5 years as hot spot temperatures and averaged values have been used for the whole calculation from the commissioning date till its end of life.

For each month, first week's 24-hour winding temperature readings have been taken and then averaged. Averaged 24-hour winding temperature characteristic for one day has been assumed to be same throughout the month.

Figure 4.21 shows the 24-hour winding temperature characteristics of Madampe Transformer 02 for the month of January for last 5 years and Figure 4.22 show the averaged 24-hour winding temperature characteristics of Madampe Transformer 02 for the month of January.

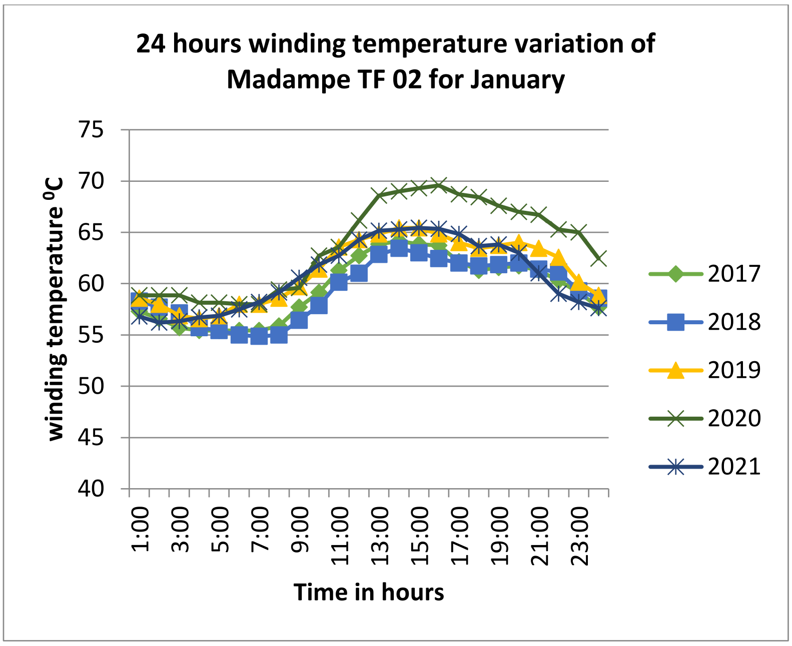


Figure 4.21 24 Hour winding temperatures of Madampe TF02 for January

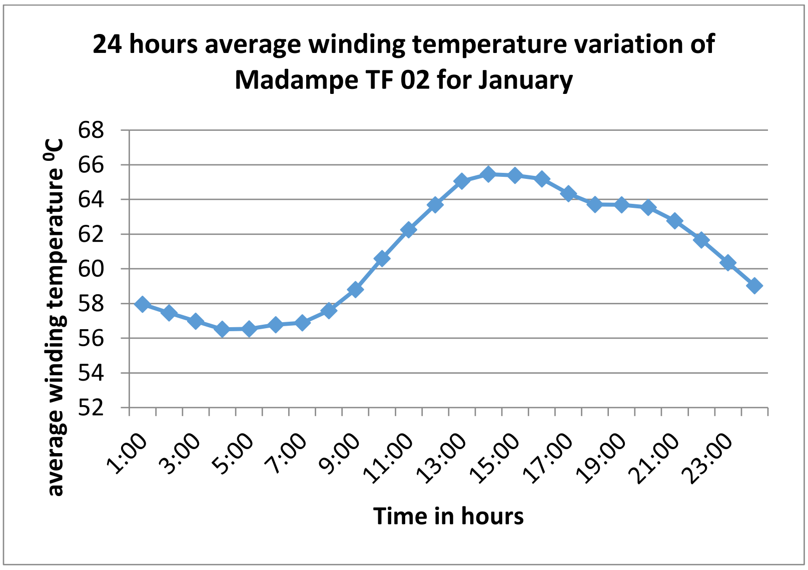


Figure 4.22 24 Hour average winding temperature of Madampe TF02 for January

Similar set of average winding temperature characteristics for all other eleven months were estimated same way. Average winding temperatures of all 3 Transformers for all 12 months are in Appendix C. Average hourly winding temperatures have been taken for the calculation of ageing rate k.

4.11.3 Calculation of k

Value of k has been calculated hourly by using ((*2-2*),

$$k = Ae^{\frac{-Ea}{RT}}$$

Where, E_a = 111 $kJmol^{-1}$,

R = 8.3145 $Jmol^{-1}K^{-1}$

T = Hot spot temperature + 273 K

Following are the two-hour calculations of Madampe Transformer 02 for January 1994.

Hour 01.00,

A = $1.28 * 10^{08}\ h^{-1}$

T = $58\ ^{0}C$

From ((*2-2*),

$$k = Ae^{\frac{-Ea}{RT}}$$

$$k = 1.28 * 10^{08} * e^{\frac{-111000}{(8.3145*(58+273))}}$$

$$k = 3.879 * 10^{-10} h^{-1}$$

Hour 02.00,

A = $1.28 * 10^{08}\ h^{-1}$

T = $57\ ^{0}C$

From ((*2-2*),

$$k = Ae^{\frac{-Ea}{RT}}$$

$$k = 1.28 * 10^{08} * e^{\frac{-111000}{(8.3145*(57+273))}}$$

$$k = 3.654 * 10^{-10} h^{-1}$$

Same calculation has been performed from the date of Transformer was energized till 31st of December 2023.

4.12 Calculation of Degree of Polymerization (DP)

As described in section 3.6 in Method Chapter, the equation ((*2-1*) has been used for the calculation of DP .

$$\frac{1}{DP(t)} - \frac{1}{DP(0)} = kt$$

Initial value of DP has been taken as 1000. DP value has been calculated hourly and calculation of DP of Madampe Transformer 2 for 2 hours in month of January 2008 is as shown below.

- DP calculation of 1.00 hour for January month

DP(0)	= DP(previous hour)
	= 465.205522
k	= $5.695 * 10^{-09}$
t	= 1 hours
No. of days in January	= 31

Thus, for 31 days in January for 1.00 hour from ((*2-1*),

$$\mathrm{DP(t)} = \frac{1}{\left(31kt + \frac{1}{DP(0)}\right)}$$

$$\mathrm{DP(1)} = \frac{1}{\left(31 * 5.695 * 10^{-09} * 1 + \frac{1}{465.205522}\right)}$$

$$\mathrm{DP(1)} = 465.167315$$

- DP calculation of 2.00 hour for January month

DP(0)	= DP(previous hour)
	= 465.167315

k = 5.364×10^{-09}

t = 1 hours

No. of days in January = 31

Thus, for 31 days in January for 2.00 hour from ((*2-1*),

$$\mathrm{DP(t)} = \frac{1}{\left(31kt \ + \ \frac{1}{DP(0)}\right)}$$

$$\mathrm{DP(2)} = \frac{1}{\left(31 * 5.364 * 10^{-09} * 1 \ + \ \frac{1}{465.167315}\right)}$$

$$\mathrm{DP(2)} = 465.131339$$

As illustrated in the flow chart in Figure 3.4, the same calculation has been carried out on hourly basis from the date of Transformer was energized till 31^{st} of December 2023. Appendix D shows the exact hourly calculation done on Madampe Transformer 02 for the year 1994. Same calculation was continued for every year.

4.12.1 Estimation of Ageing as at Now

Figure 4.23 and Figure 4.24 show the Moisture content variation of Madampe Transformer 02 and Puttalam Transformer 01 from the date of the Transformer was energized till 31^{st} of December 2023. According to the results, Madampe Transformer 02 shows rapid rise in year 2009 and 2019 due to oil leaks.

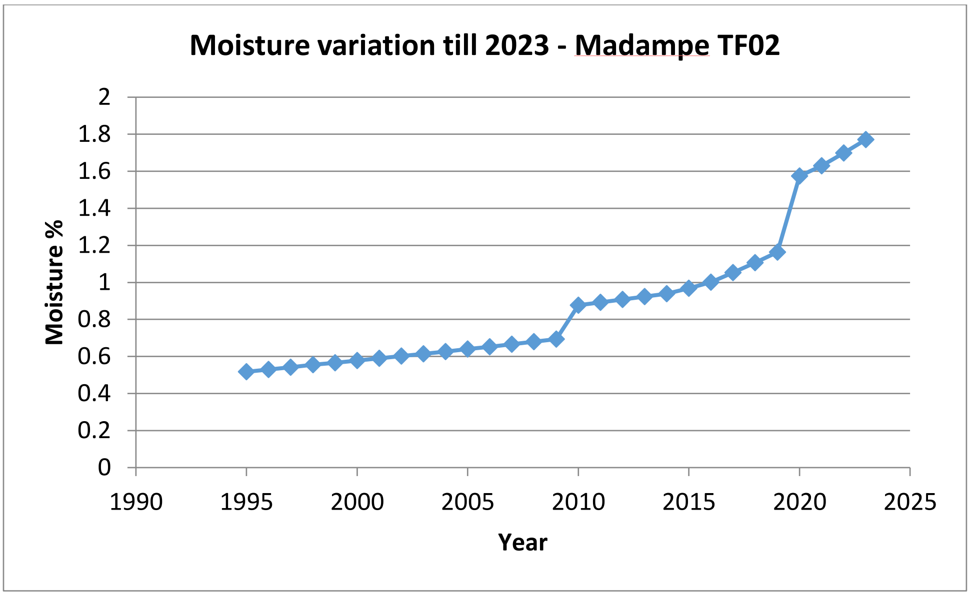


Figure 4.23 Variation of moisture content of Madampe TF02 till 2023

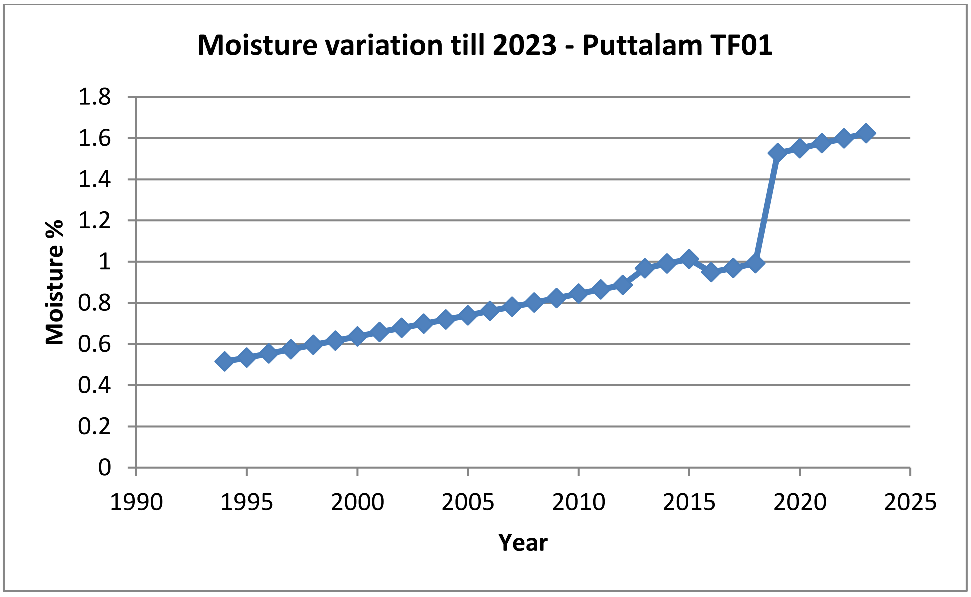


Figure 4.24 Variation of moisture content of Puttalam TF01 till 2023

Same calculation has been done for all the three Transformers and results are attached in Appendix E.

Figure 4.25 and Figure 4.26 show the DP value variation of Madampe Transformer 02 and Puttalam Transformer 01 from the date of the Transformer was energized till 31st of December 2023. DPs of both Transformers are gradually decreasing.

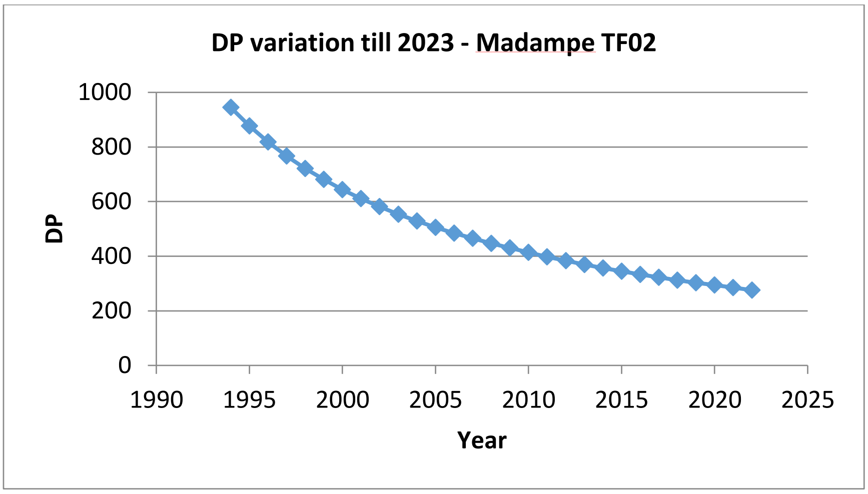


Figure 4.25 Variation of DP of Madampe TF02 till 2023

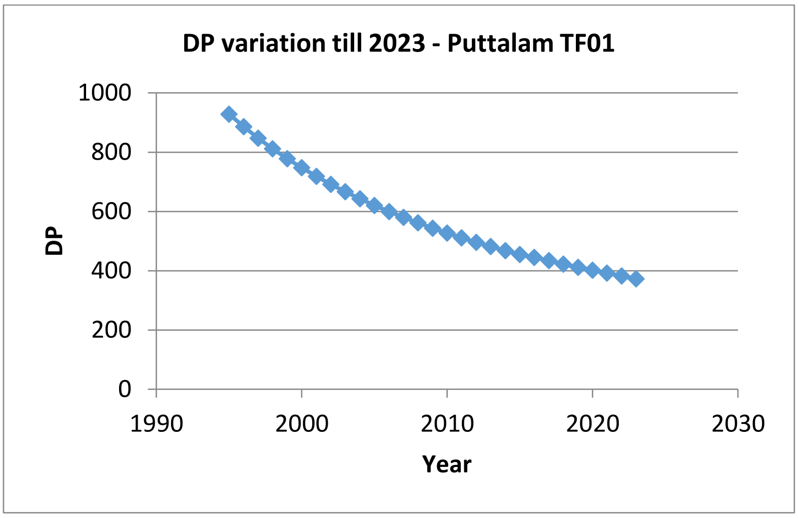


Figure 4.26 Variation of DP of Puttalam TF01 till 2023

Same calculation has been done for all the three Transformers and results are attached in Appendix F.

4.12.2 Estimation of remaining lifetime

The same calculation has been continued till DP reach to 200 which is the end of life and number of years remaining to reach 200 is taken as the remaining lifetime of the Transformers.

For the calculation of remaining lifetime, it was assumed that the load pattern of the last five year will remain unchanged throughout the period from commencement of the operation of Transformer till its end of life. Further, it was also assumed that the environmental conditions of the year 2023, remains unchanged throughout the period from commencement of its operation till the end of life.

However, the load of the Transmission Transformers varies slightly with the time due to the ever-increasing demand and augmentations in the Transmission network. Hence, the temperature of the Transformer will also increase in line with the load. In addition to that, the environmental conditions such as temperature and the relative humidity also vary with the time. Due to this reason, much better life estimation can be achieved if the predicted load and environmental conditions are used for the ageing calculation.

Figure 4.27 and Figure 4.28 show the Moisture content variation of Madampe Transformer 02 and Puttalam Transformer 01 from the date of the Transformer was energized till their end of life.

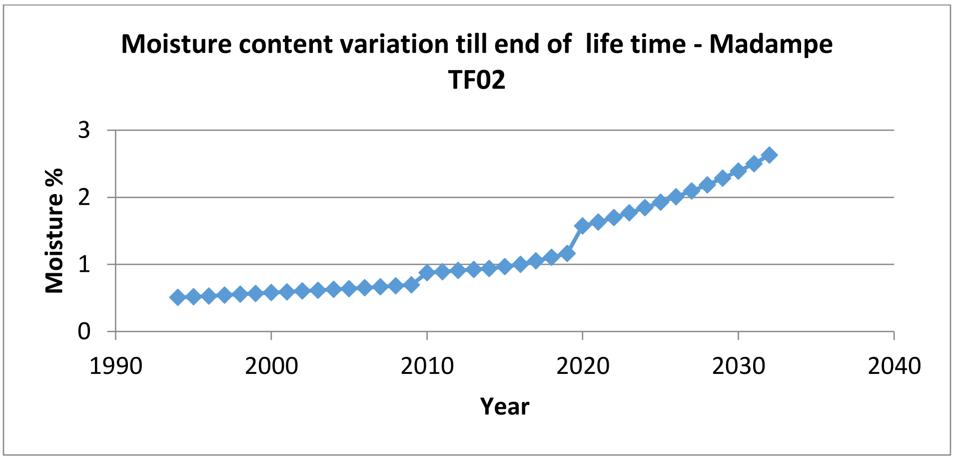


Figure 4.27 Variation of moisture content of Madampe TF02 till end of life

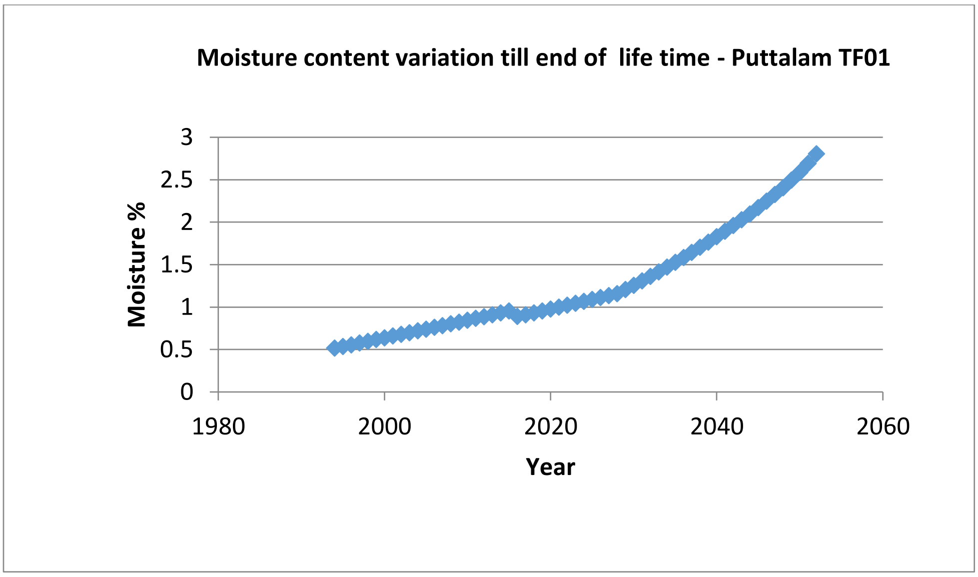


Figure 4.28 Variation of moisture content of Puttalam TF01 till end of life

Same calculation has been done for all the three Transformers and results are attached in Appendix G.

Figure 4.29 and Figure 4.30 show the DP variation of Madampe Transformer 2 and Puttalam Transformer 01 respectively till their end of life. According to the results Madampe Transformer 02 has the lifetime till 2032 and Puttalam Transformer 01 has the lifetime till 2051.

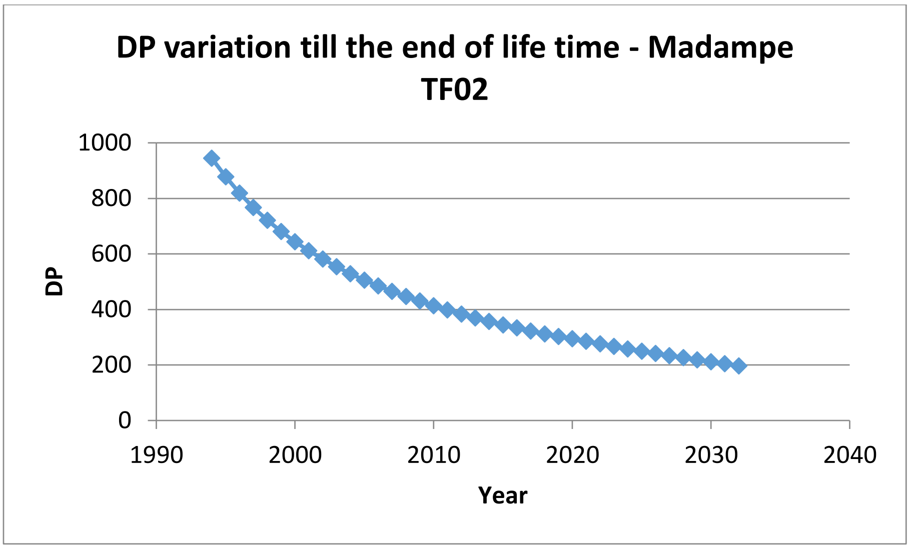


Figure 4.29 Variation of DP of Madampe TF02 till end of life

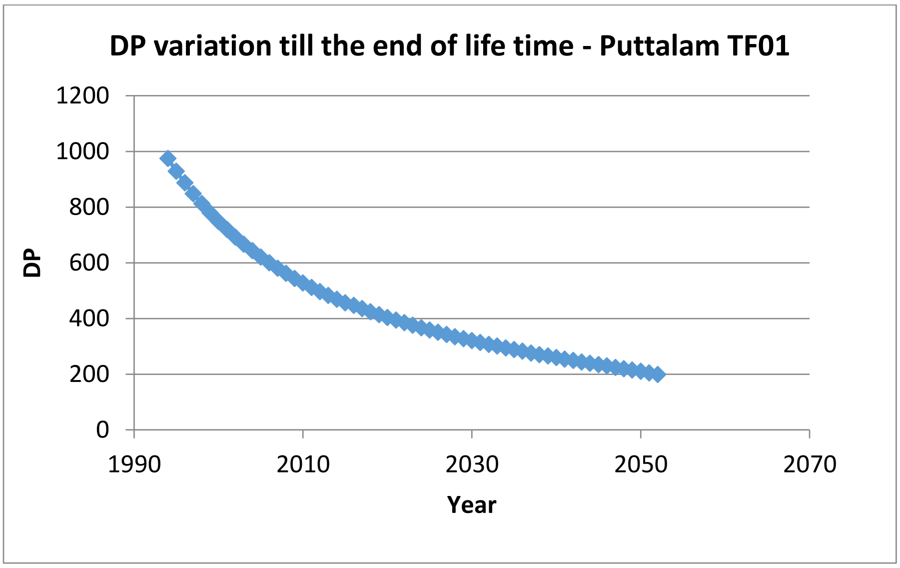


Figure 4.30 Variation of DP of Puttalam TF01 till end of life

Same calculation has been done for all the three Transformers and results are attached in Appendix H.

Table 4-13 shows the remaining life time of studied Transformers. The calculation of remaining lifetime is performed under the limitation of assuming that the same load pattern, averaged last five years hourly temperatures and environmental conditions of the year 2023 are remain unchanged throughout the period from commissioning the Transformer till its end of life.

Table 4-13 Calculated present DP, Moisture content and remaining life of TFs

	Madampe TF02	Puttalam TF01	Puttalam TF02
DP at present	270.95	377.93	272.413
M% at present	1.74	1.038	1.095
Remaining life	2032	2051	2034

4.13 Results verification through DIRANA and correction

Ageing and lifetime of Transformers have been estimated based on Degree of Polymerization. However, there is no any method of measuring the DP value of a paper sample currently available in Sri Lanka and there is no any possibility of taking a paper sample from Transformer which in operation. Hence, verification of DP is not possible. The next major parameter which was calculated is the Moisture content. Therefore, it has been decided to compare the calculated and measured moisture contents of these Transformers to verify the estimation.

Dielectric Frequency Response Analysis (DIRANA) is considered as the most accurate moisture content measuring method and instrument currently used in the industry. Thus, calculation verification has been done by comparing the DIRANA measured moisture content and calculated moisture content.

4.13.1 Estimation of Moisture % using DIRANA test

In Dielectric Frequency Response Analysis (DIRANA),dielectric dissipation factor (ratio of active and imaginary capacitance) is measured over range of frequency from 1000 Hz to 0.1mHz. During measurement Voltage signal of 200V peak with varying frequency is applied across main insulation. Then measure the resistive and capacitive current to calculate the dielectric dissipation factor.

Measured frequency response is compared with modeled frequency response using that of paper insulation sample with known moisture content and X,Y geometrical factor of Transformer main insulation system.

In general, different band of frequency response is correlated to physical properties of oil paper insulation such as very low frequency band represent the ageing and the moisture in paper insulation as well as high frequency band. Further, frequency range has -1 gradient indicates the conductivity of oil.

Figure 4.31 illustrates the general criteria of evaluating frequency response of Transformer main insulation. Overall, it is accepted that, estimated moisture content using this method is almost equal to the actual moisture content. And therefore, one can use comparison of moisture content from this method and that from ageing calculation to verify the accuracy of estimated lifetime.

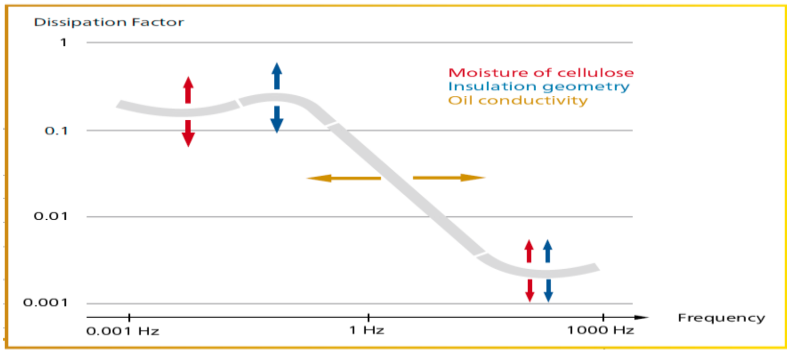


Figure 4.31 Descriptive DIRANA curve

Figure 4.32 shows DIRANA results of MadampeTF02.

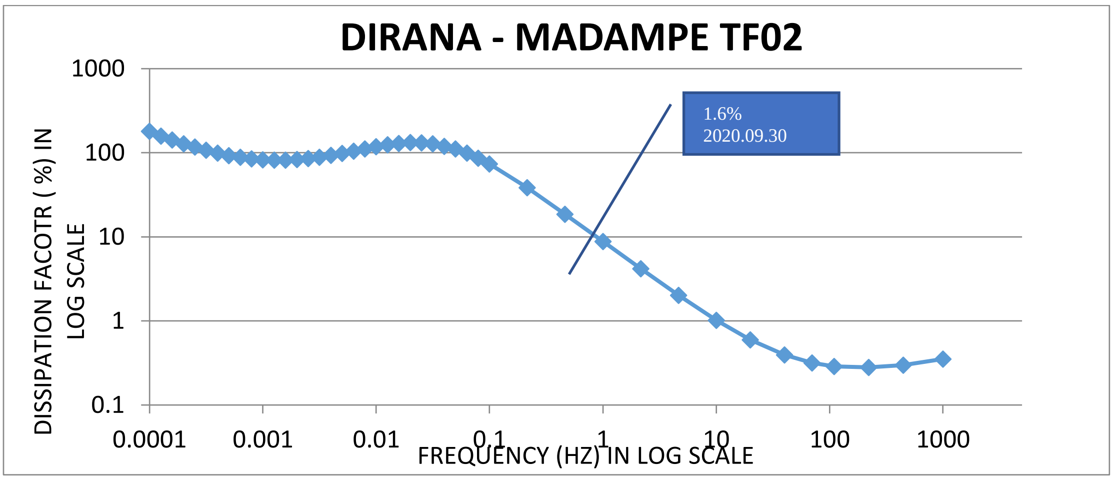


Figure 4.32 DIRANA test result of MadampeTF02

Moisture content results received from DIRANA test and calculated moisture content at same month have been tabulated in Table 4-14. All DIRANA results curves are in Appendix I.

Table 4-14 Calculated and estimated moisture content data

GS	Transformer	Moisture content	
Madampe GS	TF02	Date	20200930
		Measured	1.6%
		Calculated	1.6%
Puttalam GS	TF01	Date	20190215
		Measured	1.40%
		Calculated	0.90%
	TF02	Date	20130128
		Measured	0.80%
		Calculated	0.70%

Table 4-14 shows the measured and calculated moisture content comparison of all three Transformers and according to the results, Madampe TF2 have exactly matched with the DIRANA and other two Transformers have some small deviations.

4.13.2 Calculation of error in estimated life

In this case, it has been assumed that, moisture content given by DIRANA is correct and therefore, it has been considered that, difference between calculated moisture and estimated moisture content is due to the error of calculated life. Thus, this research calculates the time required to compensate the error between calculated and measured moisture content which is known as the calculation error of the lifetime. Table 4-15 shows the error in years.

Table 4-15 Calculation errors of Transformers

GS	Transformer	Moisture content		Error in years
		Date	**20200930**	
		Measured	1.6%	
Madampe GS	TF02	Calculated	1.6%	0
		Date	**20190215**	
		Measured	1.40%	
	TF01	Calculated	0.90%	-5
		Date	**20130128**	
		Measured	0.80%	
Puttalam GS	TF02	Calculated	0.70%	-1

4.13.3 Corrected remaining lifetime of Transformers

Table 4-16 represent the corrected remaining lifetime of all the Transformers. According to the results, Puttalam Transformer 01 have more than 20 years of remaining lifetime, while other two Transformers have less than 15 years of remaining lifetime.

Table 4-16 Corrected remaining life of Transformers

	Madampe TF02	Puttalam TF01	Puttalam TF02
DP at present	270.95	377.93	272.413
M% at present	1.74	1.038	1.095
Errors in years	0	-5	-1
Remaining life	2032	2051	2034
Corrected remaining life	2032	2046	2033

CHAPTER 5 THERMAL MODEL FOR OF AGEING POWER TRANSFORMERS

According to the calculations done in Chapter 03, the lifetimes of the Transformers depend on Temperature, Moisture and Oxygen level in the Transformer. However, if the Transformers are properly maintained, moisture does not ingress into the Transformer through oil leakages and only the inhaling and ageing of paper ingress the moisture in to the Transformer. Oxygen remains high in the Transformers as all these Transformers are free breathing type. Then the lifetime deciding main factor is the temperature which changes with the load of the Transformer, and temperature settings of the cooling fans. Therefore, in this Chapter, development of the Thermal Model is elaborated. As described in the section 3.8.2, primary objective of the thermal model is to derive the 24-hour hotspot temperature curve for the transformer through a systematic exploration of diverse fan group temperature settings and the corresponding runtimes of cooling fans. Thus, ultimately 24-hour hotspot temperature curves under different loadings, and various cooling fan group temperature settings for a specific transformer can be achieved.

5.1 Transformer Data Required for Thermal Model

As described in 3.8.2.1 section calculation of Hot Spot temperature requires weight data of transformers, Transformer alarm settings, ambient temperature of the area, load losses in different fan conditions, No load losses, load losses in different fan conditions, top oil raise over ambient at rated load, hot spot raise over ambient at rated load, and maximum load of the transformer.

5.1.1 Weight data of transformers

Wight Data of all Transformers are tabulated in Table 5-1.

Table 5-1Weight details of Transformers

Transformer	Total Mass (Tons)	Untanking Mass (Tons)	Transport Mass (Tons)	Oil Mass (Tons)
Madampe TF	65.5	36.4	57.5	16.5
PuttalamTf	54.8	27	38.5	15.3

As the density of mineral oil is 0.890 kg/l, No of oil litters in the Transformers have been calculated as below.

$$\text{Litters of oil in Madampe Transformer} = \frac{Oil\ mass}{Oil\ density}$$

$$\text{Litters of oil in Madampe Transformer} = \frac{16500\ \text{kg}}{0.890\ \text{kg/l}}$$

$$\text{Litters of oil in Madampe Transformer} = 18{,}539.33\ \text{litters}$$

Same calculation has been done for Puttalam Transformer too and results have been tabulated in the Table 5-2.

Weight of core and coil assembly is same as the untanking mass. Therefore, the weight of tank and fitting has been calculated by deducting the core and coil assembly weight and oil weight from the total weight of the Transformer.

All these results are in the Table 5-2.

Table 5-2 Calculated weight and oil capacity details of Transformers

Transformer	Total Mass (Tons)	Untanking Mass (Tons)	Transport Mass (Tons)	Oil Mass (Tons)	Oil in Litters	Core & coil Mass (Tons)	Tank and fitting Mass (Tons)
Madampe TF	65.5	36.4	57.5	16.5	18539.33	36.4	12.6
PuttalamTf	54.8	27	38.5	15.3	17191.01	27	12.5

5.1.2 Cooling methods and cooling fan temperature settings

- ONAN method

ONAN refers to the Oil Natural Air Natural cooling method. At this condition, cooling fans are disabled and heat loss of the Transformer is dissipated through natural oil circulation via the radiators.

- ONAF method

ONAF refers to the Oil Natural Air Forced cooling method. At this condition, cooling fans are in operation. Fans are operated at two stages as Group 1 and Group 2. One set of fans are running during Group 1 stage and whole set of fans are running during Group 2 stage.

- Fan running Settings

Table 5-3 shows the temperature settings which have been set for studied Transformers. When the temperature increases, Fan group 01 starts at Group 1 setting temperature and Fan group 02 starts at Group 2 setting temperature.

Table 5-3 Fan Group operation settings of Transformers

	LV setting (^{0}C)	
Transformer	**Group 1**	**Group 2**
Puttalam TF	80	90
Madampe TF	55	60

5.1.3 Factory Test Data of Transformers

Factory Acceptance Tests reports have not been available for any of these studied Transformers. Therefore, FAT reports of selected other Transformers from different venders having similar capacity and voltage ratios have been analyzed to get average values for required data of Transformers in order to calculate the Hot spot temperature.

FAT reports of following Transformers have been considered.

- Chunnakkam Transformer - PTCG make - Appendix J
- Kegalle Transformer - YOKOGAWA make - Appendix K
- Kotugoda - ABB make - Appendix L
- Maho - PTCG make - Appendix M
- Kiribathkumbura - SIEMENS make - Appendix N

Following data have been taken to calculate average value

- No load loss
- Load loss at ONAN cooling condition
- Load loss at ONAF cooling condition
- Top oil temperature raise at rated load
- Hot spot temperature raise over top oil at rated load

Table 5-4, shows the average data calculated from FAT reports of above Transformers. All the data have been taken only for the nominal tap position.

Table 5-4 FAT data of similar Transformers

Transformer	Load Loss (kW) ONAF	Load Loss (kW) ONAN	No load loss (kW)	Top oil Temp. Raise	Hot.temp. raise over ambient
Chunnakkam PTCG	119.201	63.566	19.799	47	62.6
Kegalle YOKOGAWA	113.696	-	19.743	34	
Kotugoda ABB	119.91	-	15.430	40.4	48.6
Maho PTCG	117.757	62.78	19.564	38.9	49.1
Kiribathkumbura SIEMENS	154.598	89.164	14.442	-	-
Average	117.64	63.17	18.63	40.08	53.43

These average values have been used for further calculations.

5.1.4 Calculation of data for Fan Group 1

Factory acceptance tests have been carried out only for ONAN and ONAF fan Group 2 conditions. Therefore, test data have not been available for ONAF fan Group 1 condition. Hence, test data for ONAF fan Group 1 have been calculated as below.

Rated capacity at ONAF = 31.5 MVA (From Table 4-1)

Rated load in A at ONAF at secondary side = Rated Power / Rated Voltage

= 31.5 MVA / 33 kV

= 551.12 A

Rated capacity at ONAN = 23 MVA (From Table 4-1)

Rated load in A at ONAN at secondary side = Rated Power / Rated Voltage

= 23 MVA / 33 kV

= 402.41 A

Loss of the Transformer has been represented in general by equation 5-1.

$$\text{Loss of the Transformer} = I^2R \qquad (5\text{-}1)$$

From Equation 5-1 and Table 5-4, For ONAF condition,

I^2R = Load loss at ONAF Group 2

R = Load loss at ONAF Group 2 / I^2

= 117.64 kW / $(551.12\ A)^2$

= 0.39 Ω

Heat dissipated by ONAF Group 2 = Load loss at ONAF Group 2

= 117.64 kW

Heat dissipated without any fan = Load loss at ONAN

= 63.17 kW

Thus,

Heat dissipated only by ONAF Group 2 = Load loss at ONAF – Load loss at ONAN

= 117.64 kW - 63.17 kW

= 54.47 kW

During the Fan Group 1, only the half of the fan sets is running. Hence,

Heat dissipated only by ONAF Group 1 = Heat dissipated only by ONAF Group 2 /2

= 54.47 kW / 2

= 27.23 kW

Therefore,

Heat dissipated by ONAF Group 1 = Heat dissipated only by ONAF Group 1 + Heat dissipated by ONAN

= 27.23 kW + 63.17 kW

= 90.41 kW

Thus, rated load at ONAF Group 1 (I^2R) = 90.41 kW

I = $(90.41\ kW / 0.39\ \Omega)^{1/2}$

$I = 481.48\ A$

Loss and Rated load have been tabulated in Table 5-5.

Table 5-5 Calculated Rated data for Fan Group 1 and 2

	ONAN	ONAF Fan Group 1	ONAF Fan Group 2
Rated Load (A)	402.41	481.48	551.12
Loss at rated load (kW)	63.17	90.41	117.64

5.2 Calculation of parameters related to hotspot temperature

5.2.1 Calculation of Ratio of load loss at rated load to no load loss (R)

As described in section 3.8.1 in Method Chapter, calculation of R for ONAN condition is shown below using data in Table 5-4 & Table 5-5.

$$R = \text{Load loss at rated load / No load loss}$$
$$= 63.17\ kW / 18.63\ kW$$
$$= 3.39$$

Same calculation for ONAF fans Group 1 and 2 have been done and results are tabulated in Table 5-6.

Table 5-6 Calculated 'R' values

	R
ONAN	3.39
ONAF Group 1	4.85
ONAF Group 2	6.31

5.2.2 Calculation of Thermal Capacity of Transformers

As described in section 3.8.2 in Method Chapter, Thermal Capacity of Transformers has been calculated as shown below.

From equation ((2-8) and data in the Table 5-2, Thermal capacity of Madampe Transformer for ONAN condition has been calculated as below.

$$\begin{aligned} C = {} & 0.1323(\text{weightofcoreandcoilassemblyinkg}) \\ & + 0.0882(\text{weightoftankandfittinginkg}) + 0.3513(\text{oilquantityinl}) \end{aligned}$$

$$C = 0.1323(36400) + 0.0882(12600) + 0.3513(18539.33)$$

$$C = 12{,}443.61$$

From equation ((2-9) and data in the Table 5-2, Thermal capacity of Madampe Transformer for ONAF condition has been calculated as below.

$$\begin{aligned} C = {} & 0.1323(\text{weightofcoreandcoilassemblyinkg}) \\ & + 0.1323(\text{weightoftankandfittinginkg}) + 0.5099(\text{oilquantityinl}) \end{aligned}$$

$$C = 0.1323(36400) + 0.1323(12600) + 0.5099(18539.33)$$

$$C = 15{,}935.90$$

Same calculation has been done for Puttalam Transformers too and results are tabulated in Table 5-7.

Table 5-7 Calculated 'C' values for studied Transformers

Transformer	**Oil in Litters**	**Core & coil Mass (Tons)**	**Tank and fitting Mass (Tons)**	**C for ONAN**	**C for ONAF**
Madampe TF	18539.33	36.4	12.6	12443.61	15935.90
PuttalamTf	17191.01	27	12.5	10717.24	13991.55

5.2.3 Calculation of time constant for rated load (ƮTO,R)

As described in section 3.8.3 in Method Chapter, Calculation of ƮTO,R has been calculated using data in Table 5-4 & Table 5-7. Sample calculation for Madampe Transformer for ONAN condition is shown below,

From equation ((2-7),

$$\text{Ʈ}TO,R = \frac{C\Delta\Theta TO,R}{PT,R}$$

$$\text{Ʈ}TO,R = \frac{12{,}443.61 * 40.07}{63170}$$

$$\text{Ʈ}TO,R = 7.89\text{h}$$

Same calculation at ONAF fans Group 1 and 2 have been done for all Transformers and results are tabulated in Table 5-8.

Table 5-8 Calculated Time constant

Transformer	Ʈ TO,R ONAN	Ʈ TO,R ONAF Group 1	Ʈ TO,R ONAF Group 2
Madampe TF	7.89	7.06	5.43
PuttalamTf	6.80	6.20	4.77

5.3 Hot spot temperature calculation for thermal model

5.3.1 Estimation of existing load curve

As an input to the thermal model, it is required to input the load pattern curve of the transformer. Therefore, 24 hours load data of Transformers have been collected over the last three years in operation. Load data of first week of each month have been collected. Then, average 24-hour loads have been calculated for each Transformer.

Further calculations have been done under the limitation of assuming the same load curve will remain unchanged till the end of life of Transformers.

Figure 5.1 shows the 24-hour average load curve of Madampe Transformer 02.

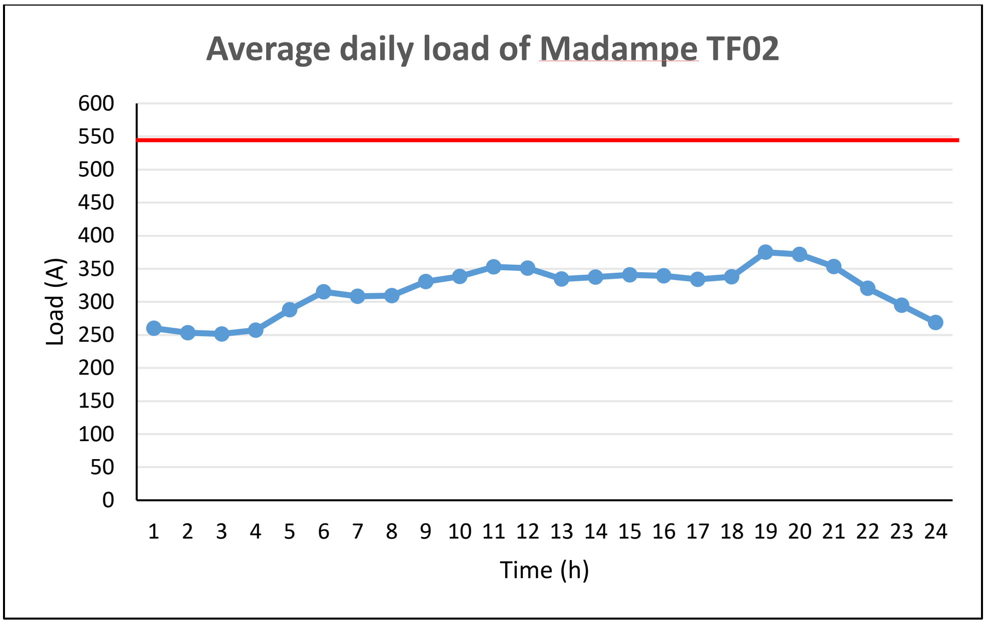


Figure 5.1 Average daily load pattern of Madampe Transformer

Average load curves of Puttalam Transformers are in Appendix O

5.3.2 Hotspot Temperature Calculation Algorithm

The hotspot temperature calculation algorithm, outlined in Section 3.8.2.1, utilizing the data computed for parameters in Section 5.1 and visualized in Figure X, is a dynamic process influenced by the operating state of the cooling fans — ONAN, ONAF – Fan Group 1, or ONAF – Fan Group 2. The equations governing hotspot calculation are adjusted based on the fan operating state, thereby accommodating variations in parameters and subsequently affecting the hotspot temperature.

The algorithm employs a feedback loop utilizing the load curve described in Section 5.3.1 as the primary input. Iteratively, the load curve is incremented by 5% in each cycle to calculate the hotspot temperature using the equations from Section 3.8.2.1. This iterative process, driven by a feedback loop, serves the dual purpose of identifying the hotspot temperature and dynamically adjusting the cooling fan settings.

A separate iterative function is employed to determine the temperatures at which Fan Group 1 and Fan Group 2 switch on. The iterative function incorporates specific conditions to establish a temperature range: Ambient Temperature < Temperature Setting of Fan Group 1 < Temperature Setting of Fan Group 2 < Alarm Temperature of the Transformer.

Consequently, the algorithm generates a 24-hour hotspot temperature curve for different loading levels and distinct cooling fan temperature settings. This comprehensive approach accounts for the dynamic interplay between load variations, cooling fan settings, and the resultant hotspot temperature.

Snaps of thermal model coded in python are in Appendix P. Further, thermal model results for Madampe 2 are in Appendix Q.

CHAPTER 6 TRANSFORMER REMAINING LIFE ESTIMATION MODEL

6.1 Introduction

As described in section 3.8.3 and visualized in Figure 3.7, the estimation of remaining life of the transformer from January 2024 is done. The 24-hour hotspot temperature curve, which is the output of the thermal model was used in calculating the DP values, instead of using the historical transformer temperature data. The objective of this sub model is to deliver the new transformer life for all the combinations of increased load percentages, fan settings, and hot spot temperature curves.

6.2 Function of the Model

To initiate the DP calculation through transformer remaining life estimation model values from the historic data driven transformer calculation model were assigned to the respective parameters.

The following values were initially assigned for Puttalam Transformer 1 for remaining life time estimation.

- DP Values as at now (December 2023) = 375.02
- Total Moisture as at now (December 2023) = 1.045727
- O2 Level – High

Thereafter, as per Figure 3.4 the DP calculation was carried out hourly.

As terminating factors of the iterative model two terminating conditions were set. They are ‘Maximum transformer age equals 50 years’ or ‘DP value equals 200’ and depends on which comes first, iterative function is terminated.

Therefore, this model will output new transformer life for each 24-hour hotspot temperature curve. For Madampe TF-2, 1325 combinations of 24-hour hotspot temperature curves, cooling fan settings, percentage loadings, and new estimated transformer lifetime was received through the model.

Snaps of transformer life estimation model coded in python are in Appendix R. Further, transformer life estimation model results for Madampe 2, Puttalam 1 & Puttalam 2 are in Appendix S respectively.

Further, the combinations of results for Madampe TF 2 are in Appendix T.

CHAPTER 7 COST OPTIMATION MODEL

7.1 Introduction

As outlined in the section 3.8.4, the main objective of the cost optimization model is to find the optimum solution from total combinations generated by the transformer life estimation model. The cost-benefit analysis was used as the base for the cost optimization model.

7.2 Costs of Implementation of the Model

There are two major cost components need to be considered for cost benefit analysis, which are load losses and auxiliary losses.

7.2.1 Load Losses

In the iterative function of the thermal model, the initial load curve has been increased at 5% rate to find the optimum loading capability of the transformer while maintaining the set conditions. Therefore, due to this increased loading there will be increased Cu losses (Load Losses).

The calculation for the load losses is carried upon as outlined in section 3.8.4.2

The calculation for Puttalam TF 2 is as below;

At the time of calculation, Temperature settings of Fan group 1 is 36 ^{0}C, Temperature settings of Fan group 2 is 60 ^{o}C, and the loading is 30% of the initial loading. Further, estimated transformer life time for the mentioned settings were year 2037. Based on that calculation is carried out.

Load Loss for the month (kWh) $= \sum ((Load_h)^2$ x TF winding resistance x 30/1000)

Load loss for the entire month with new load (30% 0f initial load) = 47,920.2 kWh

Load loss for the entire month with initial load = 28,355.14 kWh

The unit cost is considered as 48 Rs/kWh , and the discount rate is considered as 10%.

Therefore, NPV of additional load losses due to the proposed methodology can be calculated as below,

$$NPV\ of\ Additional\ Load\ Loss\ Cost$$
$$= NPV\ (\ monthly\ load\ loss\ cost\ with\ new\ load, new\ tf\ life\ with\ settings)$$
$$- NPV\ (monthly\ load\ loss\ cost\ with\ initial\ load, tf\ life\ with\ original\ settings)$$

Therefore,

NPV of Additional Load Loss Cost = LKR 111,059,197.86

7.2.2 Auxiliary Losses

In the iterative function of the thermal model, cooling fan temperature settings have been changed to get different combinations of fan group settings. Therefore, at each iteration run time of cooling fan group 1 and cooling group 2 have been increased. Therefore, due to the increased operation of cooling fans, auxiliary losses of the transformer have increased, which is a considerable cost to the utility.

The calculation for the auxiliary losses is carried upon as outlined in section 3.8.4.1

The calculation for Puttalam TF 2 is as below

There are 3 numbers of 3 kW fans are running at Fan Group 1, and 6 numbers of 3 kW fans are running at Fan Group 2. At the same conditions mentioned in section 7.2.1, cooling fan group 1 runs for 3 hours per day, while cooling fan group 2 runs for 21 hour a day. Therefore, auxiliary cost per month with the new settings can be calculated as below;

Auxiliary Loss (kWh) = Run time of cooling Fan Group 1 & Fan Group 2 x power of a fan (kW) x number of cooling fans x unit cost

= (9 x 3 hours + 18 x 21 hours) x 30 x 48

= LKR 583,200

Auxiliary cost per month with the initial settings can be calculated as below;

Auxiliary Loss (kWh) = Run time of cooling Fan Group 1 & Fan Group 2 x power of a fan (kW) x number of cooling fans x unit cost

= (9 x 3 hours + 18 x 01 hours) x 30 x 48

= LKR 64,800

Similarly, maintenance aspect of the cooling fans is also considered. Cost per fan per hour based on running time of cooling fans are considered.

Cost of a cooling fan is considered as LKR 752,000, and maintenance cost of existing cooling fan is considered to be Rs 12.43 per fan per hour. This value was considered based on the 12 hours running time of a fan per day having 14 years of lifetime.

Therefore, the maintenance cost can be calculated as;

Maintenance cost = (FG2_runtime_total_value + (FG1_runtime_total_value + FG2_runtime_total_value))*30*Cost_per_Fan_per_hour*3

Maintenance cost at Initial Setting = (3+4) x 30 x 12.43 * 3 = LKR 5595.278

Maintenance cost at New Setting = LKR 50,357.14

Therefore, the NPV of additional auxiliary loss cost including maintenance cost can be calculated as;

$$NPV\ of\ Additional\ Auxiliary\ Loss\ Cost = NPV\ (monthly\ auxliary\ loss\ cost\ including\ maintenance\ cost\ with\ new\ settings\ ,\ new\ tf\ life\ with\ settings) - NPV\ (monthly\ auxliary\ loss\ cost\ including\ maintenance\ cost\ with\ initial\ settings\ ,\ tf\ life\ with\ original\ settings)$$

$$NPV\ of\ Additional\ Auxiliary\ Loss\ Cost = LKR\ 55{,}840{,}102.07$$

7.3 Benefit of Implementation of the Model

There are two major benefit components (cost savings) need to be considered for cost benefit analysis, which are cost saving due to deferred replacement cost and cost saving due to increased loads.

7.3.1 Transformer Cost Calculation

In order to do the net benefit calculation of this cost optimization model, it is required to use transformer costs and transformer cost per MVA per year values. Therefore, previously purchased transformers by CEB was collected and done the calculations and taken average values of Transformer costs and transformer cost per MVA per year.

Table 7-1 Cost Figures of Transformers

Year	TF	Voltage Level	MVA	Avg. Lifetime TF	Cost in USD	Inflation Factor	Inflation Adjusted Cost (USD)	USD/MVA	USD/MVA per year
2020	PTCG	220/33	63	35	1520000	1.2782	1,942,864	30,839	881.1
2020	BEST	220/33	63	35	1500000	1.2782	1,917,300	30,433	869.5
2020	JSHP	220/33	63	35	1250000	1.2782	1,597,750	25,361	724.6
2020	TBEA	220/33	63	35	1100000	1.2782	1,406,020	22,318	637.7
2022	Siyambalanduwa	132/33	63	35	2650000	1	2,650,000	42,063	1,201.8
2016	Kerawalapiti	220/33	63	35	928139.5	2.088316	1,938,249	30,766	879.0
2016	Kesbewa	132/33	31.5	35	570316.8	2.088316	1,191,002	37,810	1,080.3
2016	Kalutara	132/33	31.5	35	550964.5	2.088316	1,150,588	36,527	1,043.6
Average Costs							**1,724,221**	**32,015**	**915**

The values on the Table 7-1 has been used for calculation of deferred replacement cost and saving due to increased loads.

7.3.2 Deferred replacement cost

From the proposed model it will generate set of new loadings, and cooling fan temperature settings that have increased the estimated transformer life time, from the anticipated transformer life time with the existing settings. Therefore, replacement of the existing transformer can be delayed. A utility company can potentially benefit from deferring the replacement of the transformer.

The calculation for the deferred replacement cost is carried upon as outlined in section 3.8.4.4

The calculation for Puttalam TF 2 is as below;

$$\text{NPV of Previous Replacement Cost} = \frac{\text{Average Transformer Cost}}{(1+Dicount\ rate)^{(previous\ life\ time+1)}}$$

$$= \frac{1{,}724{,}221*300}{0.4399} \quad = \text{LKR } 227{,}534{,}897.80$$

$$\text{NPV of New Replacement Cost} = \frac{\text{Average Transformer Cost}}{(1+Dicount\ rate)^{(New\ life\ time+1)}}$$

$$= \frac{1{,}724{,}221*300}{0.26963} \quad = \text{LKR } 139{,}472{,}758.01$$

Saving due to differed replacement cost = $Prev.Replacement\ Cost - New\ Replacement\ Cost$

= LKR 88,062,139.79

7.3.3 Saving due to increased loads

Improvement in the loading of the transformer and by improving the utilization of the existing transformer, utility company can potentially save purchasing of an additional MVA capacity transformer.

The calculation for the saving due to increased loads is carried upon as outlined in section 3.8.4.3

The calculation for Puttalam TF 2 is as below

Previous Loading cost =

$$\sum(\sqrt{3}\ X\ Transformer\ Secondary\ Voltage\ X\ Load)X\ Average\ MVA\ cost\ of\ Transformer)\ X\ 30\ X\ Lifetime\ of\ Tranformer$$

Previous Loading cost = LKR 299,834,928.32

New Loading cost =

$$\sum(\sqrt{3}\ X\ Transformer\ Secondary\ Voltage\ X\ Load)X\ Average\ MVA\ cost\ of\ Transformer)\ X\ 30\ X\ New\ Lifetime\ of\ Tranformer$$

New Loading cost = LKR 389,785,407.81

Saving Due to Increased Loads = $\text{NPV(New Loading cost, New Lifetime)} - \text{NPV(Previous Loading cost, Previous Lifetime)}$

Saving Due to Increased Loads = LKR 14,159,236,459.75

7.4 Net Benefit Calculation

Net benefit based on the proposed settings by the model was then calculated. It was done using the following equation;

$$NPV\ of\ Net\ Benefit = Deferred\ Replacment\ cost + Saving\ due\ to\ increased\ loads - Auxiliary\ losses - Load\ losses$$

$$NPV\ of\ Net\ Benefit = MLKR\ 14{,}080\ .40$$

Similar to the above calculation, for all cooling fan temperature settings, and percentage loadings, net benefit NPV calculation was performed, and identified the optimized solution from the model. Therefore, the model output will identify the most economically viable cooling fan settings for ageing transformers to improve their lifetime along with the improved loading.

Snaps of transformer cost optimization model coded in python are in Appendix U. Further, cost optimization model results for Madampe 2, Puttalam 1 & Puttalam 2 are in Appendix V respectively.

CHAPTER 8 RESULTS AND ACCURACY OF THE MODEL

8.1 Results

The integration of the three mathematical models—namely, the thermal model, transformer remaining life estimation model, and cost optimization model— provides a comprehensive array of outcomes. These results include different costs for a specific transformer and the life time of transformer, showing various combinations of cooling fan settings, cooling fan operation hours, and transformer loads. The output of the model presents a panoramic view of possibilities to increase the loading of transformers and improve their lifetime by having combinations of cooling fan settings. Thus, the model outcomes help to understand, and make informed decisions on how to manage transformers more effectively.

Firstly, the thermal model determines combinations of cooling fan settings to maintain safe temperature levels, factoring in ambient conditions, load profiles, and increased loadings. Ultimately it offers insights into the number of hours cooling fan should operate with new cooling fan settings and new loading, ensuring effective heat dissipation and preventing transformer overheating. Secondly, the transformer remaining life estimation model forecasts the remaining lifespan of transformers, considering current cooling fan settings, increased loads, and environmental factors. Finally, the cost optimization model calculates financial implications encompassing maintenance costs, energy consumption, and potential savings derived from extending transformer life. This prediction aids in strategizing maintenance schedules and replacement plans.

Based on the results of the cost optimization model the top 10 optimized solutions for each transformer under the scope was considered.

Table 8-1 Top 10 optimized solutions for Madampe Transformer 2

Temp _FG1	**Temp _FG2**	**Increased Load%**	**Runtime Hours_ ONAN**	**Runtime Hours_ FG1**	**Runtime Hours_ FG2**	**TF End of life - Years**	**NPV (MLKR)**
36	52	5	0	2	22	2042	5,197.46
40	52	5	0	2	22	2042	5,197.46
44	52	5	0	2	22	2042	5,197.46

48	52	5	0	2	22	2042	5,197.46
36	56	5	0	6	18	2040	4,184.48
40	56	5	0	6	18	2040	4,184.48
44	56	5	0	6	18	2040	4,184.48
48	56	5	0	6	18	2040	4,184.48
52	56	5	1	4	19	2040	4,123.30
52	52	5	2	0	22	2040	3,996.68

In Table 8-1, it shows the 10 optimized solutions based on the calculated NPV out of all the combinations for Madampe Transformer 2. Based on the optimized solution, with the mentioned new fan group settings, it is able to increase 5% more of the initial load of the transformer, and transformer end of life can be increased up to 2042, which is more than 5 years from the expected model output with the original fan settings.

Table 8-2 Top 10 optimized solutions for Puttalam Transformer 1

Temp _FG1	**Temp _FG2**	**Increased Load%**	**Runtime Hours_ ONAN**	**Runtime Hours_ FG1**	**Runtime Hours_ FG2**	**TF End of Life - Years**	**NPV (MLKR)**
36	60	30	0	3	21	2047	23142.24
40	60	30	0	3	21	2047	23142.24
44	60	30	0	3	21	2047	23142.24
48	60	30	0	3	21	2047	23142.24
52	60	30	0	3	21	2047	23142.24
56	60	30	0	3	21	2047	23142.24
36	60	35	0	2	22	2045	23803.34
40	60	35	0	2	22	2045	23803.34
44	60	35	0	2	22	2045	23803.34

48	60	35	0	2	22	2045	23803.34
52	60	35	0	2	22	2045	23803.34
56	60	35	0	2	22	2045	23803.34

In Table 8-2, it shows the 10 optimized solutions based on the calculated NPV out of all the combinations for Puttalam Transformer 1. Based on the optimized solution, with the mentioned new fan group settings, it is able to increase 30% - 35% more of the initial load of the transformer, and transformer end of life can be increased up to 2047, which is more than 9 years from the expected model output with the original fan settings.

Table 8-3 Top 10 optimized solutions for Puttalam Transformer 2

Temp _FG1	Temp _FG2	Increased Load%	Runtime Hours_ ONAN	Runtime Hours_ FG1	Runtime Hours_ FG2	TF End of Life - Years	NPV (MLKR)
36	60	30	0	3	21	2037	14080.4
40	60	30	0	3	21	2037	14080.4
44	60	30	0	3	21	2037	14080.4
48	60	30	0	3	21	2037	14080.4
52	60	30	0	3	21	2037	14080.4
56	60	30	0	3	21	2037	14080.4
36	60	35	0	2	22	2036	13986.43
40	60	35	0	2	22	2036	13986.43
44	60	35	0	2	22	2036	13986.43
48	60	35	0	2	22	2036	13986.43
52	60	35	0	2	22	2036	13986.43
56	60	35	0	2	22	2036	13986.43

In Table 8-3, it shows the 10 optimized solutions based on the calculated NPV out of all the combinations for Puttalam Transformer 2. Based on the optimized solution, with the mentioned new fan group settings, it is able to increase 30% - 35% more of the initial load of the transformer, and transformer end of life can be increased up to 2037, which is more than 5 years from the expected model output with the original fan settings.

Table 8-4 Summary of predicted transformer life with new settings

Transformer	**Description**	**Loading**	**Cooling Fan Temp. Setting**		**Fan Runtime (h)**			**TF End of Life - Year**
			FG 1	**FG 2**	**ONAN**	**FG1**	**FG 2**	
Madampe TF 2	Original Parameter	Initial	55	60	2	13	8	2037
	New Parameters	5%	36	52	0	2	22	2042
			40	52	0	2	22	
			44	52	0	2	22	
			48	52	0	2	22	
Puttalam TF 1	Original Parameter	Initial	80	90	19	3	1	2038
	New Parameters	30%	36	60	0	3	21	2047
			40	60	0	3	21	
			44	60	0	3	21	
			48	60	0	3	21	
			52	60	0	3	21	
			56	60	0	3	21	
Puttalam TF 2	Original Parameter	Initial	80	90	19	3	1	2032

	New Parameters	30%	36	60	0	3	21	2037
			40	60	0	3	21	
			44	60	0	3	21	
			48	60	0	3	21	
			52	60	0	3	21	
			56	60	0	3	21	

The summary of the cooling fan settings, and the predicted best transformer life of the transformers with optimum loading are tabulated in Table 8-4. Therefore, it is possible to reach the optimum output using different cooling fan settings. Further, the model will have different combinations of loadings, and cooling fan settings that will provide different transformer lifetime in years with economic feasibility. Therefore, this model will assist the utility to make informed decisions based on the requirements, and to make informed decisions on transformer management and retirement, preventing catastrophic failures.

8.2 Accuracy of the Model

8.2.1 Model Prediction Accuracy

The calculation of prediction accuracy for the model involves comparing the predicted transformer lifetime output generated by the model, which described in chapter 5 and chapter 6, with the verified transformer lifetime calculated using established methods described in chapters 4. Both were considered at original fan settings and the present loading of the transformer. To quantify the accuracy, mean absolute percentage error and mean absolute prediction accuracy was used. This was performed for all the transformers under the scope and are in Table 8-5.

Table 8-5 Model Prediction Accuracy

Transformer	Original Fan Setting		Verified Life Time	Model Output	Error%	Model Prediction Accuracy
	FG 1	FG2				
Madampe TF 2	55	60	2032	2037	13.16	86.84
Puttalam TF2	80	90	2033	2032	2.56	97.44

Puttalam TF1	80	90	2046	2038	15.38	84.62
Mean Absolute Prediction Error & Mean Absolute Prediction Accuracy					10.37	89.63

Therefore, the model prediction accuracy is about 90%, and it signifies a satisfactory performance of the model in predicting transformer lifetimes. This level of accuracy suggests that the model is effective in estimating transformer lifetimes under the given conditions and parameters.

8.2.2 Model Parameter Sensitivity

Parameter sensitivity analysis is a critical step in building reliable and trustworthy prediction models. It not only improves the model's robustness but also provides valuable insights into the behavior of the model and its dependencies on various factors. Sensitivity analysis for a prediction model involves assessing how changes in input parameters or model assumptions affect the model's output or predictions. It helps identify which factors have the most significant impact on the model's results and can provide insights into the model's robustness and reliability.

The main inputs, ambient temperature, moisture level, and percentage loading was considered for parameter sensitivity analysis. The calculation was performed for Madampe transformer 2.

Ambient temperature was varied from 28 ^{o}C to 37 ^{o}C, and change in model predicted transformer life was calculated, and tabulated in Table 8-6.

Table 8-6 Sensitivity Analysis - Ambient Temperature

Temperature	FG 1	FG2	Load %	FG 1	FG 2	Tr Life Time
28	55	60	5	13	10	2036
29	55	60	5	12	11	2035
30	55	60	5	12	12	2035
31	55	60	5	5	18	2035
32	55	60	5	4	19	2034
33	55	60	5	4	19	2033
34	55	60	5	3	21	2032
35	55	60	5	3	21	2031
36	55	60	5	2	22	2031
37	55	60	5	2	22	2030

As per the Table 8-6, the sensitivity of transformer life time due to ambient temperature is -66.67%. Since the sensitivity value is high, ambient temperature can be considered as a highly sensitive input parameter to the model.

Moisture in air is also varied from 22 g/m^3 to 38 g/m^3, and change in model predicted transformer life was calculated, and tabulated in Table 8-7

Table 8-7 Sensitivity Analysis – Moisture in Air

Moisture (g/m3)	Fan Settings		Fan Runtime		TF Life
	FG 1	FG2	FG1	FG2	
22	56	60	17	5	2037
26	56	60	17	5	2037
30	56	60	17	5	2036
34	56	60	17	5	2036
38	56	60	17	5	2035

As per the Table 8-7, the sensitivity of transformer life time due to moisture in air is -12.5%. Since the sensitivity value is low, moisture in air can be considered as a low sensitive input parameter to the model.

Percentage loading is varied from 5% to 40% from the initial load, and change in model predicted transformer life was calculated, and tabulated in Table 8-8.

Table 8-8 Sensitivity Analysis - Loading

Increased Load%	Fan Setting		Fan Runtime		TF Lifetime
	FG1	FG2	FG1	FG2	
5	55	60	13	10	2036
10	55	60	11	12	2035
15	55	60	8	16	2034
20	55	60	8	16	2032
25	55	60	1	22	2031
30	55	60	3	21	2030
35	55	60	2	22	2028
40	55	60	2	22	2027
45	55	60	1	23	2027

As per the Table 8-8, the sensitivity of transformer life time due to loading is -22.5%. Since the sensitivity value is the second highest, percentage loading can be considered as a moderate sensitive input parameter to the model.

CHAPTER 9 CONCLUSION

9.1 Summary and Conclusion

In conclusion, this thesis addresses the critical challenges associated with aging transformers in the Sri Lankan Power System and proposes a comprehensive methodology for optimizing their operational lifespan in a cost-efficient manner. The research highlights the significance of addressing the issues of aging, underutilization, and rising electricity demand to ensure the reliability and sustainability of the power system.

The study emphasizes the importance of understanding the aging process of transformer insulation, particularly the irreversible nature of paper insulation degradation, which accounts for a significant portion of transformer failures globally. By including all the three major parameters, such as moisture, oxygen exposure, and hot spot temperature variations into the aging study, this research aims to provide a more accurate assessment of transformer condition and remaining operational lifespan.

Through the development of a comprehensive mathematical model, the thesis proposes strategies for extending transformer lifespan and optimizing load increment by adjusting cooling fan group temperature settings. These strategies aim to mitigate temperature rise, prevent accelerated aging, and minimize energy consumption, ultimately reducing the financial burden of new transformer procurement and ensuring the long-term reliability of the power system.

The proposed methodology is grounded in scientific research and addresses the specific challenges faced by utility companies and industrial sectors in managing aging transformers. By estimating remaining transformer lifetime, assessing environmental factors, determining optimum fan group settings, and developing proactive maintenance strategies, the study provides a practical framework for maximizing the utility of aging transformers while optimizing costs over their remaining operational life.

Overall, this research contributes to the advancement of transformer management practices and lays the foundation for future studies in transformer aging and optimization. The findings of this thesis have the potential to benefit utility companies, policymakers, and stakeholders in the power sector by enhancing the reliability, sustainability, and cost-effectiveness of power transmission and distribution systems.

According to the model output, Madampe Transformer 2, Puttalam Transformer 1, and Puttalam Transformer 2 expected to have their end of life on 2037,2038, and 2032 respectively. However, with the new cooling fan settings, and increased loading those transformers expected to have their end of life on 2042, 2047, and 2037 respectively. Therefore, the top 10 optimized solutions for each transformer, presented in the results, demonstrate the potential benefits of adjusting cooling fan settings and increasing loading. These solutions highlight the opportunity to extend transformer lifespan while optimizing costs, contributing to operational efficiency and reliability.

The accuracy of the model was evaluated using mean absolute percentage error and mean absolute prediction accuracy, indicating a satisfactory performance in predicting transformer lifetimes. Parameter sensitivity analysis revealed the varying impact of input parameters, with ambient temperature showing high sensitivity, moisture in air exhibiting low sensitivity, and percentage loading demonstrating moderate sensitivity.

For the calculation of remaining lifetime, and in the model, it has been assumed that the load pattern of the last five year remain unchanged throughout the period from commencement of the Transformer till its end of life. Further, it was also assumed that the environmental conditions of the year, remains unchanged throughout the period from commencement of its operation till the end of life.

However, the load of the Transmission Transformers varies slightly with the time due to the ever-increasing demand and augmentations in the Transmission network. Hence, the temperature of the Transformer will also increase in line with the load. In addition to that, the environmental conditions such as temperature and the relative humidity also vary with the time. Due to this reason, much better life estimation can be achieved if the predicted load and environmental conditions are used for the ageing calculation.

As per the model results, it was found that the three transformers can be loaded from 5-35% from the initial load without decreasing the lifetime of the transformers, by adjusting the cooling fan group settings. Further, it was identified that by limiting moisture ingress into the transformer, and by limiting oxygen exposure transformer life time can be increased.

It is recommended to use the calculations derived including all the three major parameters, as a method of estimating the life time of the other transformers in the CEB transmission network. It will assist to make informed-decisions on removing the transformers from the transmission networks before any catastrophically failures, that it will lead to substantial cost saving.

Further, It is recommended to use the developed mathematical model to identify the most effective cooling fan group settings for life extension and load increment of ageing transformers, in such a way that cost it optimized.

9.2 Suggestion for Future Projects

Followings are suggested to study on the future projects.

- Moisture absorption efficiency of silica gel changes with the absorbed moisture. Hence, moisture absorption characteristic is a dynamic one. However, that dynamic characteristic has not been taken into this study. Hence, it is suggested to consider the dynamic behavior of moisture absorption by silica gel during the future projects.

- It is suggested to study the effect of introducing variable speed fans for transformer cooling, and improving the transformer lifetime.
- Loading pattern of Transmission Transformers and Generation Transformers are different from each other. Hence, the temperature pattern is also different. This study has been done only on Transmission Transformers. Therefore, it is suggested to study the lifetime of generation Transformers in future projects.

REFERENCES

[1] L. E. Lundgaard, W. Hansen, D. Linhjell, and T. J. Painter, "Ageing of Oil-Impregnated Paper in Power Transformers," *IEEE Trans. Power Deliv.*, vol. 19, no. 1, pp. 230–239, 2004, doi: 10.1109/TPWRD.2003.820175.

[2] S. Tenbohlen, J. Jagers, and F. Vahidi, "Standardized survey of transformer reliability: On behalf of CIGRE WG A2.37," *Proc. Int. Symp. Electr. Insul. Mater.*, vol. 2, no. December, pp. 593–596, 2017, doi: 10.23919/ISEIM.2017.8166559.

[3] H. P. Moser, V. Dahinden, and H. Brechna, *Transformerboard II: Properties and Application of Transformerboard of Different Fibres*. 1987.

[4] J. Fabre and a. Pichon, "Deteriorating Processes and Products of Paper in Oil Application to Transformers," *CIGRE Sess. 1960*, vol. 33, no. 0, 1960.

[5] "Moisture Equilibrium and Moisture Migration within Transformer insulation systems" CIgre WG A2.30, 2008.

[6] V. Griffin, Paul Soklov, "MOISTURE EQUILIBRIUM AND MOISTURE MIGRATION WITHIN TRANSFORMER INSULATION SYSTEM Paul Griffin (Doble Engineering Co) Victor Sokolov , Boris Vanin (ZTZ – Service , Co)," *BuenoMak*, pp. 1–23.

[7] N. Lelekakis, J. Wijaya, D. Martin, T. Saha, D. Susa, and C. Krause, "Ageing rate of grade 3 presspaper insulation used in power transformers," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 5, pp. 2355–2362, 2014, doi: 10.1109/TDEI.2014.004266.

[8] A. M. Emsley, R. J. Heywood, M. Aii, and X. Xiao, "Degradation of cellulosic insulation in power transformers. Part 4: Effects of ageing on the tensile strength of paper," *IEE Proc. Sci. Meas. Technol.*, vol. 147, no. 6, pp. 285–289, 2000, doi: 10.1049/ip-smt:20000644.

[9] N. Lelekakis, D. Martin, and J. Wijaya, "Ageing rate of paper insulation used in power transformers Part 1: Oil/paper system with low oxygen concentration," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 6, pp. 1999–2008, 2012, doi: 10.1109/TDEI.2012.6396958.

[10] A. M. Emsley and G. C. Stevens, "Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers," *IEE Proc. Sci. Meas. Technol.*, vol. 141, no. 5, pp. 324–334, 1994, doi: 10.1049/ip-smt:19949957.

[11] L. E. Lundgaard, W. Hansen, and S. Ingebrigtsen, "Ageing of mineral oil impregnated cellulose by acid catalysis," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 2, pp. 540–546, 2008, doi: 10.1109/TDEI.2008.4483475.

[12] I. Höhlein and A. J. Kachler, "Ageing of cellulose at transformer service temperatures. Part 2. Influence of moisture and temperature on degree of polymerization and formation of furanic compounds in free-breathing systems," *IEEE Electr. Insul. Mag.*, vol. 21, no. 5, pp. 20–24, 2005, doi: 10.1109/MEI.2005.1513426.

[13] L. Yang, R. Liao, C. Sun, J. Yin, and M. Zhu, "Influence of vegetable oil on the thermal ageing rate of kraft paper and its mechanism," *2010 Int. Conf. High Volt. Eng. Appl. ICHVE 2010*, pp. 381–384, 2010, doi: 10.1109/ICHVE.2010.5640746.

[14] L. E. Lundgaard, W. Hansen, S. Ingebrigtsen, D. Linhjell, and M. Dahlund, "Ageing of Kraft paper by acid catalyzed hydrolysis," *2005 IEEE Int. Conf. Dielectr. Liq. ICDL 2005*, pp. 381–384, 2005, doi: 10.1109/icdl.2005.1490105.

[15] A. EMSLEY, R. HEYWOOD, M. ALI, and C. ELEY, "On the kinetics of degradation of cellulose," *Cellulose*, vol. 4, no. 1, pp. 1–5, 1997, doi: 10.1023/A:1018408515574.

[16] A. M. Emsley and G. C. Stevens, "Kinetics and mechanisms of the low-temperature degradation of cellulose," *Cellulose*, vol. 1, no. 1, pp. 26–56, 1994, doi: 10.1007/BF00818797.

[17] IEEE C57.91^{TM}-2011, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators - Redline*, vol. 2011, no. March. 2012.

[18] "Mineral transformer oil [SubsTech]." [Online]. Available: https://www.substech.com/dokuwiki/doku.php?id=mineral_transformer_oil.

[19] "Chilaw weather." Climate Weather Averages." [Online]. Available:

https://www.worldweatheronline.com/chilaw-weather-averages/north-western/lk.aspx

[20] "Puttalam weather." Climate Weather Averages." [Online]. Available: https://www.worldweatheronline.com/puttalam-weather-averages/north-western/lk.aspx

[21] "Dankotuwa Town Climate Weather Averages." [Online]. Available: https://www.worldweatheronline.com/dankotuwa-town-weather-averages/north-western/lk.aspx

[22] R. Humidity, "Water Content against Temperature for constant Relative Humidity," *M. Jankovec al., "In-Situ Monit. Moisture Ingress PV Modul. Using Digit. Humidity Sensors," IEEE J. Photovoltaics, vol. 6, no. 5, pp. 1152-1159, Sept. 2016, doi 10.1109/JPHOTOV.2016.2583779.*

[23] P. Koestinger, E. Aronsen, and P. Boss, "Practical Experience With the Drying of Power Transformers in the Field, Applying the Lfh** Technology," *Cigré*, vol. Report A2-, p. 8, 2004.

[24] D. Yu, S. a Klein, D. Ph, and D. T. Reindl, "An Evaluation of Silica Gel for Humidity Control in Display Cases," *Waac*, vol. 23, no. 2. pp. 1–18, 2001.

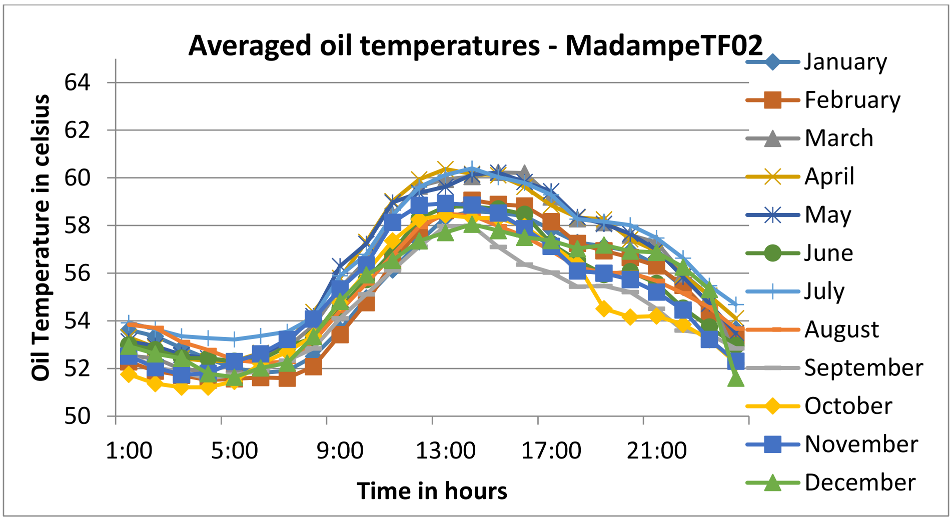
[25] "Saturated Salt Solutions and control of Air Humidity." [Online]. Available:https://www.engineeringtoolbox.com/salt-humidity-d_1887.html.

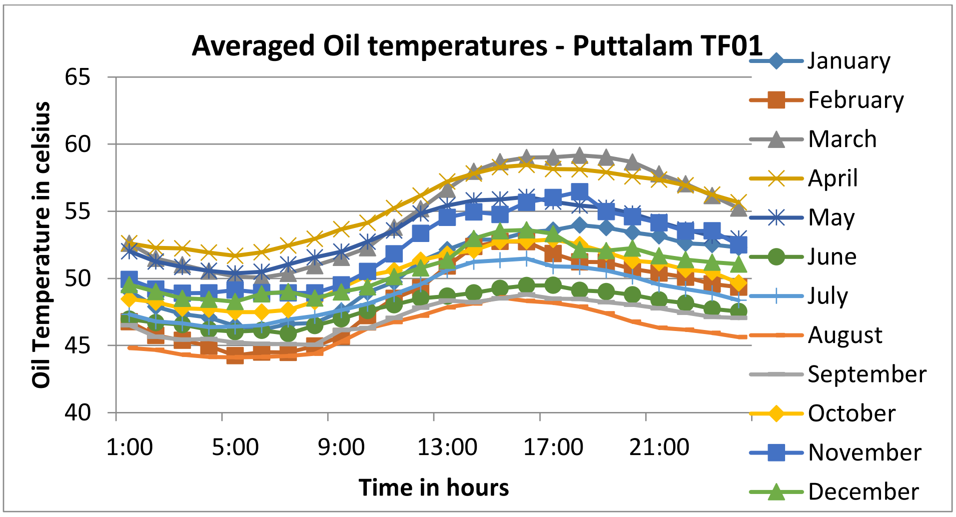
[26] "Estimation of ageing of transformer paper insulation" S.K.K.B Ekanayake, Masters thesis, University of Peradeniya, Sri Lanka, 2021 .

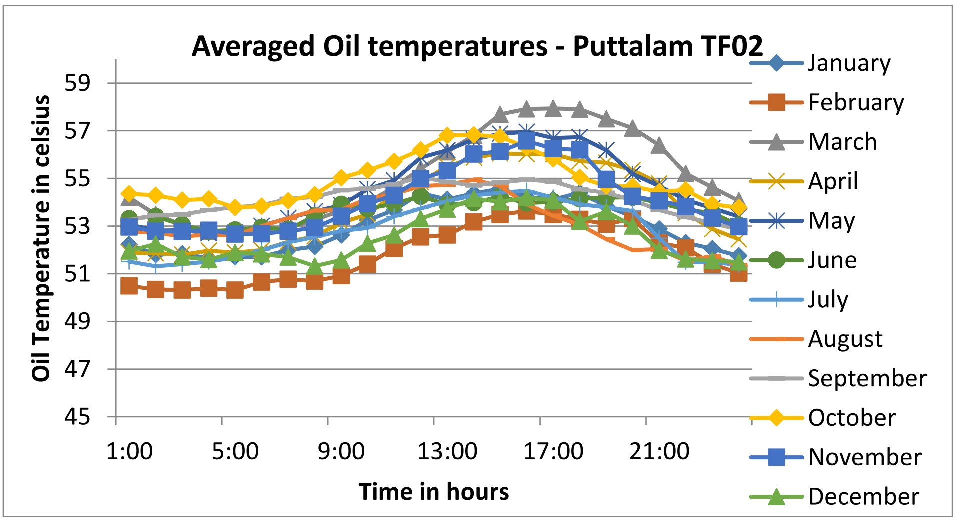
[27] "Bio degradable oil filled Transformers" K.M. Kapila Bandara, Doctorial thesis, University of Quensland, Austrailia, 2016 .

[28] B. Fallou, Summary of Work done at L.C.I.E. on the Paper -Oil complex. Internal report of Laboratoire Centre des Industries Electriques, France.

Appendix A - Average oil temperatures of the three TFs for 12 months







Appendix B - Special Maintenance report of oil filtering of Bolawatta TF

SPECIAL MAINTENANCE REPORT

Location :Bolawatta Grid Substation

Maintenance :Temperature Indicator Calibration of an EBG Transformer

Date : March / April, 2019

Serial No. (TF) :137576

Year of Manufacture: 1986

1.0. General

31.5MVA Transformer bearing serial No.137576 at Bolawatta GS was removed and replaced by a conditioned upheld similar type of Transformer which was removed from Kiribathkumbura GS. Conservator tank, two radiators and connecting oil pipes from conservator to main tank and diverter tank have removed while removing the Transformer and kept at switched yard in Bolawatta GS as it is until it reaches its thermal equilibrium. Oil of the Transformer was taken out till the oil level dropped down to top level of the radiators and kept in a separate skid tank.

Then the condition of oil was monitored on 2019.01.09 and followings were the results.

	Result	Temperature (^{0}C)
Dielectric Strength	60.9 kV / 2.5mm	30
Moisture Content	10 PPM	27.6
Relative Saturation	13.5 %	27.6

Moisture percentage in paper was calculated as 2.85%, based on above results and graph in Annex 01.

Hence, it was decided to carry out offline oil filtering on this Transformer for two weeks in order to reduce the moisture content in the Transformer and then to keep this as a spare one.

Accordingly, Transmission operation and maintenance – North Central has carried out the offline oil filtering on Transformer bearing serial No.137576 at Bolawatta GS for two weeks fromFebruary07, 2019 to February 20, 2019 with circulating the oil about 86 cycles. While filtering, all the radiators were covered with tarpaulins and temperature of the Transformer was maintained up to 65 ^{0}C.

Followings were the results just after the oil filtering.

	Result	Temperature (^{0}C)
Dielectric Strength	72.6 kV / 2.5mm	35
Moisture Content	13 PPM	57.7
Relative Saturation	6 %	57.7

Then the Transformer was kept to reach the thermal equilibrium and condition of the oil was monitored again on 2019.03.07. Followings are the results.

	Result	Temperature (^{0}C)
Dielectric Strength	74.8 kV / 2.5mm	32
Moisture Content	8 PPM	30.9
Relative Saturation	9.6 %	30.9

Moisture percentage in paper was calculated as 2.2%, based on above results and graph in Fig.3.2.

As the condition of the Transformer has been improved by dropping the Moisture percentage down to 2.2% from 2.85%, it was decided to reconnect remaining removed components of the Transformer to keep it as a spare.

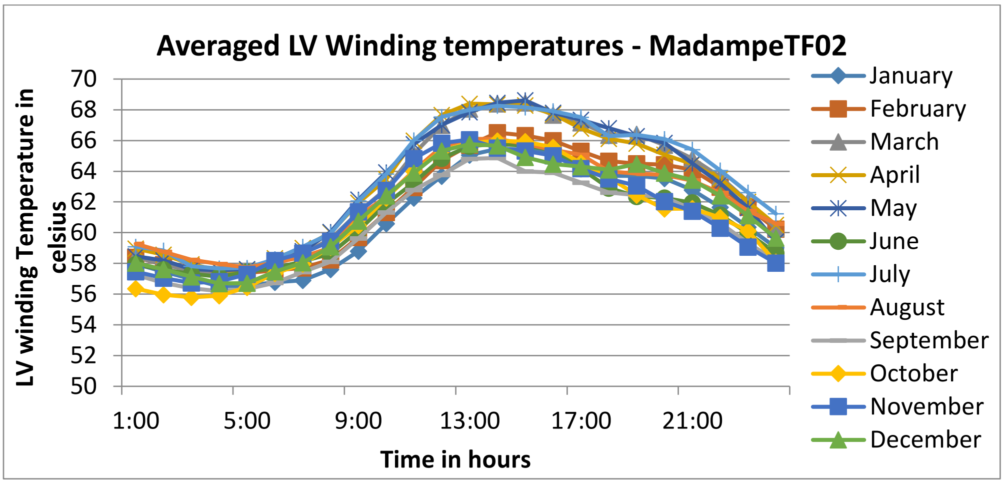
Accordingly, Transmission operation and maintenance – North Central has carried out the installation of removed components of Transformer bearing serial No.137576 at Bolawatta GS on March 19, 2019. Key steps of this work are illustrated in section 2 with photographs.

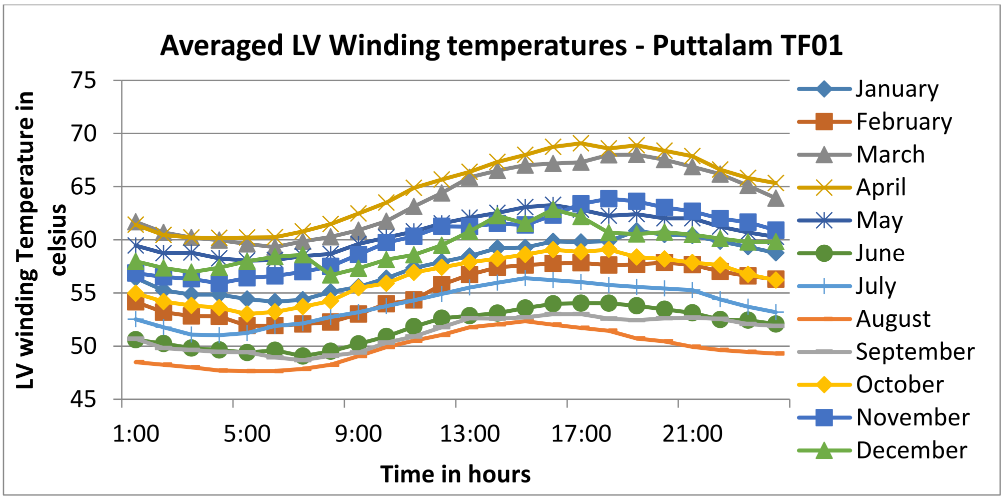
2.0. Maintenance Procedure

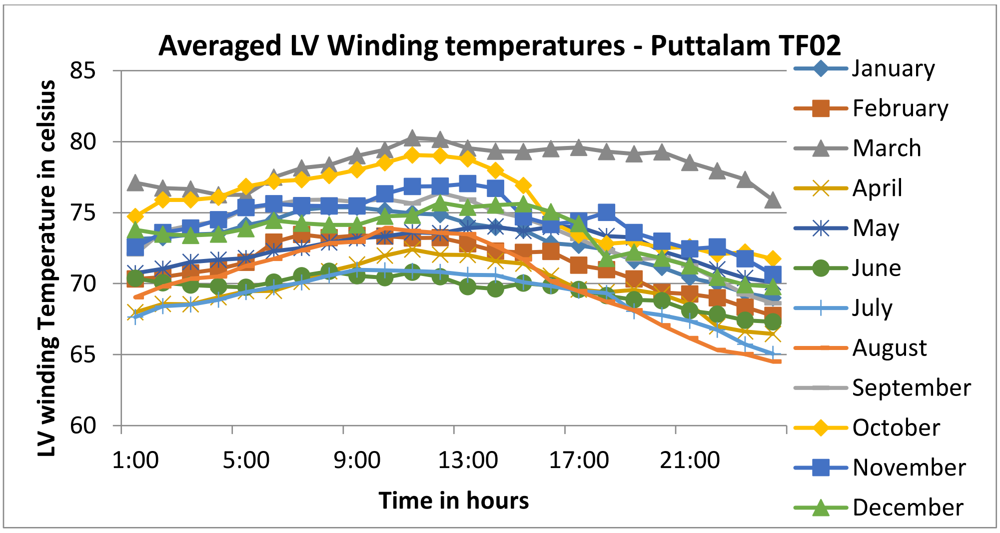
2.1. Two radiators were installed after removing the cover plates installed at radiator connecting pipes.

2.2. Inside of the conservator tank was cleaned with oil and then installed.

Appendix C - Average LV winding temperatures of 6 TFs for 12 months







Appendix D - Hourly ageing calculation and moisture calculation of Madampe TF 02 (1994)

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
RS% at Madampe	74	73	75	77	79	82	82	82	81	80	79	79
Ambient temp. Day	31	32	32	32	31	30	29	29	29	30	31	30
Ambient temp. Night	23	24	25	26	27	26	26	25	25	25	25	24
Average ambient temp.	27	28	28.5	29	29	28	27.5	27	27	27.5	28	27
Moisture in air at atmosphere	22	22	22	23	23	22	22	22	22	22	22	22
Temp Variation	7	8	8	8	8	6	7	6	6	7	7	6
Volume Change	0.0973	0.1112	0.1112	0.1112	0.1112	0.083	0.0973	0.0834	0.0834	0.0973	0.0973	0.0834
Moisture went inside	66.382	68.523	75.865	76.755	79.314	55.06	66.382	56.899	55.063	66.382	64.241	56.899
Moisture absorbed by breather	63	63	63	63	63	63	63	63	63	63	63	63
Dissolved moisture in TF	3.38247	5.52384	12.8656	13.7556	16.3141	0	3.38247	0	0	3.38247	1.2411	0
Moisture due to ageing	0	0.10951	1.28411	1.68054	2.15991	3.68165	6.24685	6.08584	5.43887	6.66353	7.09536	8.08176

Moisture removed from Offline Filtering												
Moisture removed from Online Filtering												
Hence Moisture % in paper	0.5000	0.5002	0.5005	0.5014	0.5023	0.5035	0.5037	0.5043	0.5046	0.5050	0.5056	0.5061
Accumulated air Volume went inside	2.33604	5.0058	7.67556	10.3453	13.0150	15.0174	17.3534	19.3557	21.3580	23.6941	26.0301	28.0324
%of air w.r.t. oil volume	12.6	27	41.4	55.8	70.2	81	93.6	104.4	115.2	127.8	140.4	151.2
Hence O2 level	L	L	M	M	M	H	H	H	H	H	H	H

Month	Time	O2	H20 %	wind Temp.	oil Temp.	Hots pot temp	A at low o2 and dry paper	Corrected A for O2 & H2O	k	DP(t)
Jan	1.00	Low	0.5000	58	54	58	1.28E+08	1.28E+08	3.8794E-10	999.9879741
	2.00		0.5000	57	53	57	1.28E+08	1.28E+08	3.6535E-10	999.9766486
	3.00		0.5000	57	53	57	1.28E+08	1.28E+08	3.4418E-10	999.9659797
	4.00		0.5000	57	52	57	1.28E+08	1.28E+08	3.2501E-10	999.9559051
	5.00		0.5000	57	52	57	1.28E+08	1.28E+08	3.2616E-10	999.9457952
	6.00		0.5000	57	52	57	1.28E+08	1.28E+08	3.3603E-10	999.9353794
	7.00		0.5000	57	52	57	1.28E+08	1.28E+08	3.4066E-10	999.9248204
	8.00		0.5000	58	53	58	1.28E+08	1.28E+08	3.7127E-10	999.9133131
	9.00		0.5000	59	54	59	1.28E+08	1.28E+08	4.2965E-10	999.8999965
	10.00		0.5000	61	55	61	1.28E+08	1.28E+08	5.3382E-10	999.8834516
	11.00		0.5000	62	56	62	1.28E+08	1.28E+08	6.5058E-10	999.8632886
	12.00		0.5000	64	57	64	1.28E+08	1.28E+08	7.7034E-10	999.8394152
	13.00		0.5000	65	58	65	1.28E+08	1.28E+08	9.0478E-10	999.8113768
	14.00		0.5000	65	59	65	1.28E+08	1.28E+08	9.4801E-10	999.7820006

	15.00		0.5000	65	59	65	1.28E+08	1.28E+08	9.4171E-10	999.7528211
	16.00		0.5000	65	58	65	1.28E+08	1.28E+08	9.1795E-10	999.7243793
	17.00		0.5000	64	58	64	1.28E+08	1.28E+08	8.3173E-10	999.6986104
	18.00		0.5000	64	57	64	1.28E+08	1.28E+08	7.7207E-10	999.6746913
	19.00		0.5000	64	57	64	1.28E+08	1.28E+08	7.719E-10	999.6507787
	20.00		0.5000	64	57	64	1.28E+08	1.28E+08	7.5748E-10	999.6273137
	21.00		0.5000	63	56	63	1.28E+08	1.28E+08	6.915E-10	999.6058936
	22.00		0.5000	62	55	62	1.28E+08	1.28E+08	6.0576E-10	999.5871304
	23.00		0.5000	60	54	60	1.28E+08	1.28E+08	5.1831E-10	999.5710764
	24.00		0.5000	59	54	59	1.28E+08	1.28E+08	4.4202E-10	999.5573858
Feb	1.00	Low	0.5002	58	52	58	1.28E+08	1.28E+08	4.0938E-10	999.5459334
	2.00		0.5002	58	52	58	1.28E+08	1.28E+08	3.8588E-10	999.5351387
	3.00		0.5002	58	52	58	1.28E+08	1.28E+08	3.7527E-10	999.5246412
	4.00		0.5002	57	52	57	1.28E+08	1.28E+08	3.5736E-10	999.5146447
	5.00		0.5002	57	52	57	1.28E+08	1.28E+08	3.6113E-10	999.5045431

	6.00		0.5002	58	52	58	1.28E+08	1.28E+08	3.6877E-10	999.4942278
	7.00		0.5002	58	52	58	1.28E+08	1.28E+08	3.7658E-10	999.4836944
	8.00		0.5002	58	52	58	1.28E+08	1.28E+08	4.0093E-10	999.47248
	9.00		0.5002	60	53	60	1.28E+08	1.28E+08	4.7834E-10	999.4591006
	10.00		0.5002	61	55	61	1.28E+08	1.28E+08	5.8162E-10	999.4428332
	11.00		0.5002	63	56	63	1.28E+08	1.28E+08	7.0585E-10	999.4230919
	12.00		0.5002	65	58	65	1.28E+08	1.28E+08	8.6895E-10	999.3987899
	13.00		0.5002	66	59	66	1.28E+08	1.28E+08	9.7544E-10	999.3715111
	14.00		0.5002	67	59	67	1.28E+08	1.28E+08	1.0722E-09	999.3415294
	15.00		0.5002	66	59	66	1.28E+08	1.28E+08	1.0482E-09	999.3122201
	16.00		0.5002	66	59	66	1.28E+08	1.28E+08	1.0084E-09	999.2840248
	17.00		0.5002	65	58	65	1.28E+08	1.28E+08	9.3258E-10	999.2579506
	18.00		0.5002	65	57	65	1.28E+08	1.28E+08	8.6364E-10	999.2338052
	19.00		0.5002	64	57	64	1.28E+08	1.28E+08	8.4647E-10	999.210141
	20.00		0.5002	64	57	64	1.28E+08	1.28E+08	8.4082E-10	999.1866358

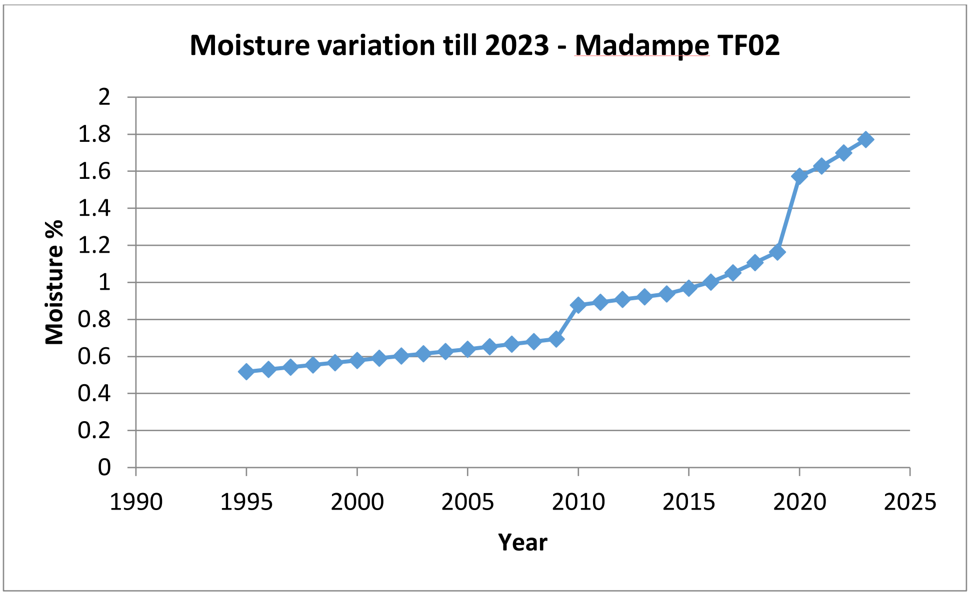
	21. 00		0.50 02	64	56	64	1.28E+ 08	1.28E+ 08	8.076 5E-10	999.164 0589
	22. 00		0.50 02	63	55	63	1.28E+ 08	1.28E+ 08	7.082 4E-10	999.144 2618
	23. 00		0.50 02	62	54	62	1.28E+ 08	1.28E+ 08	6.059 1E-10	999.127 3258
	24. 00		0.50 02	60	53	60	1.28E+ 08	1.28E+ 08	5.106 6E-10	999.113 0524

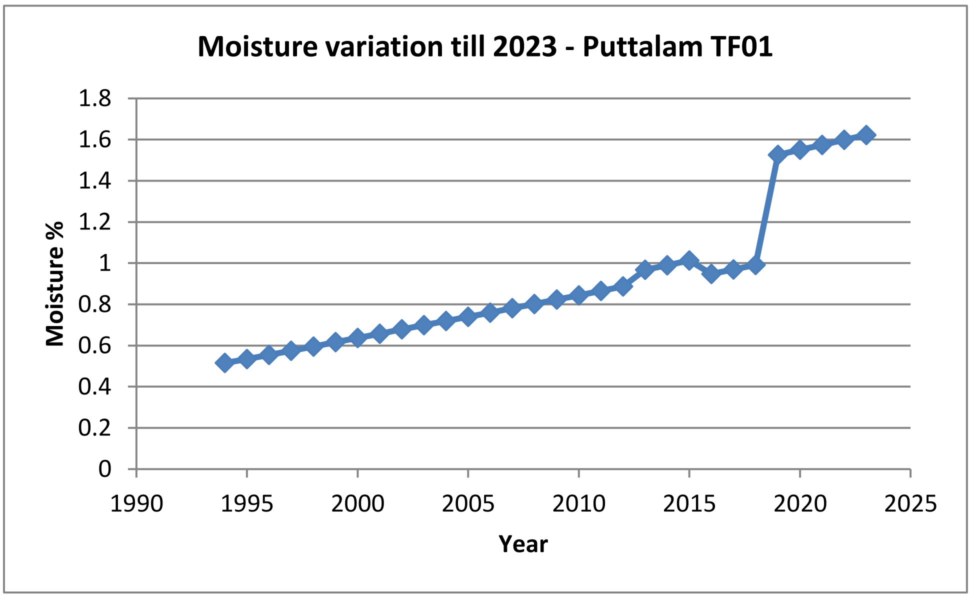
Mar	1.00	Medi um	0.50 05	58	53	58	1.28E +08	9.26E +08	2.972 2E- 09	999.021 0868
	2.00		0.50 05	58	52	58	1.28E +08	9.26E +08	2.791 8E- 09	998.934 7172
	3.00		0.50 05	58	52	58	1.28E +08	9.26E +08	2.658 8E- 09	998.852 4773
	4.00		0.50 05	57	52	57	1.28E +08	9.26E +08	2.558 5E- 09	998.773 3518
	5.00		0.50 05	57	52	57	1.28E +08	9.26E +08	2.640 3E- 09	998.691 7106
	6.00		0.50 05	58	53	58	1.28E +08	9.26E +08	2.821 1E- 09	998.604 4916
	7.00		0.50 05	59	53	59	1.28E +08	9.26E +08	3.045 3E- 09	998.510 3606
	8.00		0.50 05	60	54	60	1.28E +08	9.26E +08	3.425 2E- 09	998.404 5062

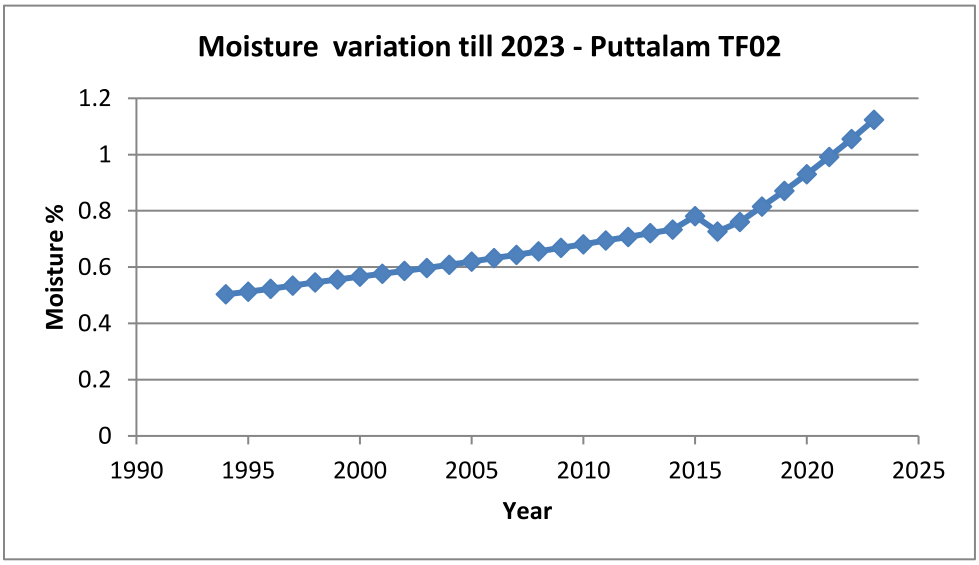
	9.00		0.5005	61	55	61	1.28E+08	9.26E+08	4.208E-09	998.2744911
	10.00		0.5005	63	57	63	1.28E+08	9.26E+08	5.0553E-09	998.1183425
	11.00		0.5005	65	58	65	1.28E+08	9.26E+08	6.6136E-09	997.9141347
	12.00		0.5005	67	60	67	1.28E+08	9.26E+08	8.2053E-09	997.6608962
	13.00		0.5005	68	60	68	1.28E+08	9.26E+08	9.2672E-09	997.3750374
	14.00		0.5005	68	60	68	1.28E+08	9.26E+08	9.6388E-09	997.0778912
	15.00		0.5005	68	60	68	1.28E+08	9.26E+08	9.702E-09	996.7789729
	16.00		0.5005	68	60	68	1.28E+08	9.26E+08	8.8509E-09	996.5064344
	17.00		0.5005	67	59	67	1.28E+08	9.26E+08	8.3692E-09	996.2488644
	18.00		0.5005	66	58	66	1.28E+08	9.26E+08	7.6129E-09	996.0146876
	19.00		0.5005	66	58	66	1.28E+08	9.26E+08	7.6652E-09	995.7790138
	20.00		0.5005	66	58	66	1.28E+08	9.26E+08	7.0597E-09	995.5620548

	21.00		0.5005	65	57	65	1.28E+08	9.26E+08	6.368E-09	995.3664347
	22.00		0.5005	64	56	64	1.28E+08	9.26E+08	5.5436E-09	995.1962011
	23.00		0.5005	62	55	62	1.28E+08	9.26E+08	4.5845E-09	995.0554622
	24.00		0.5005	60	53	60	1.28E+08	9.26E+08	3.7137E-09	994.941486

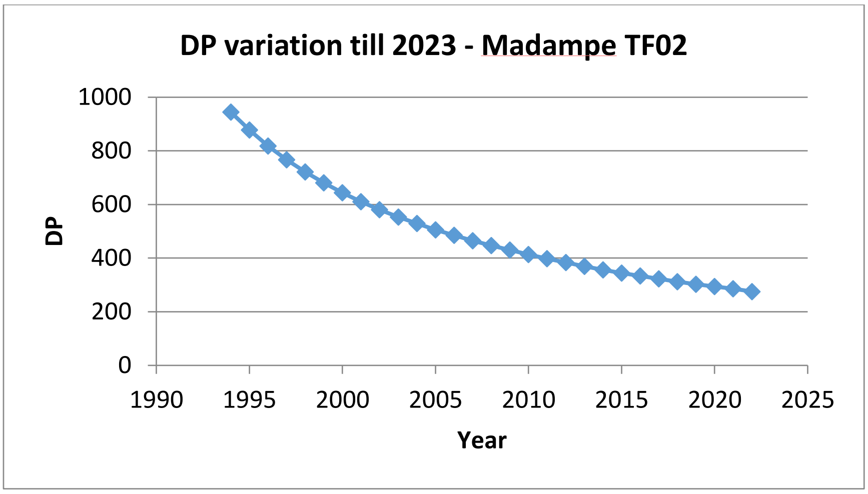
Appendix E - Moisture content variations till 2023

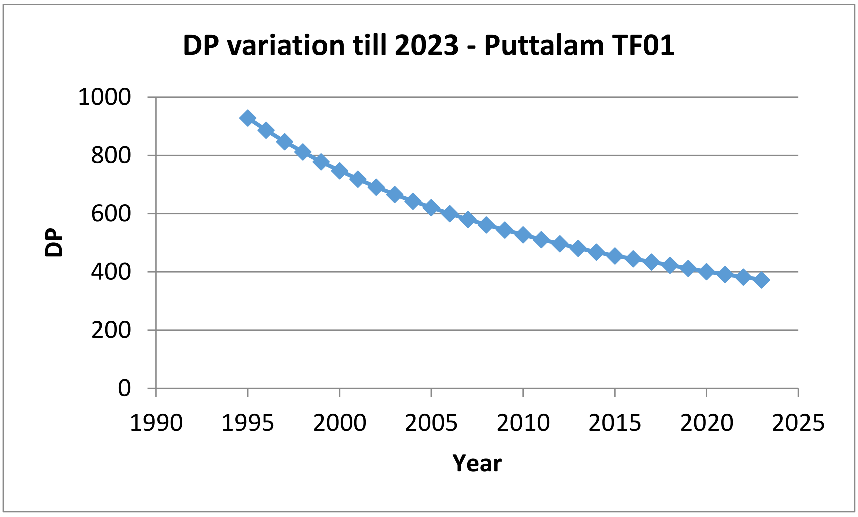


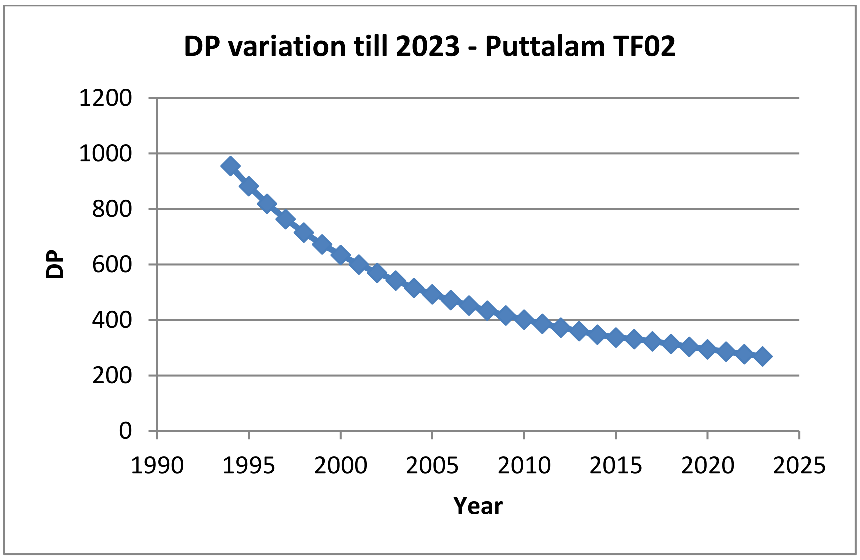




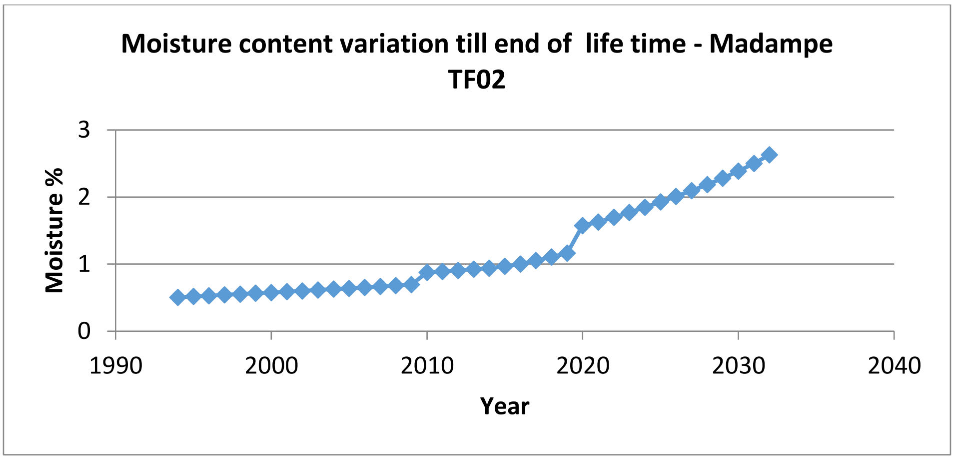
Appendix F - DP variations till 2023

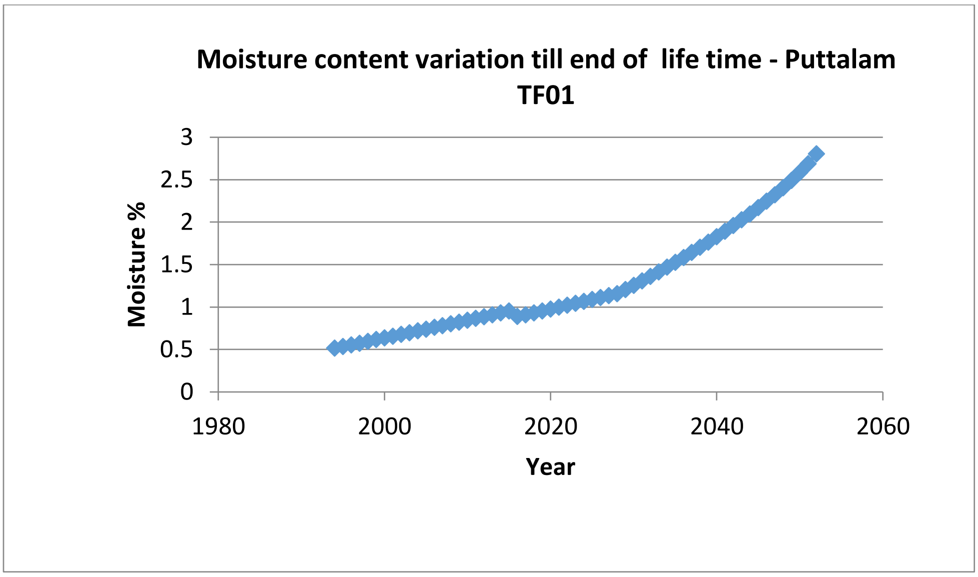


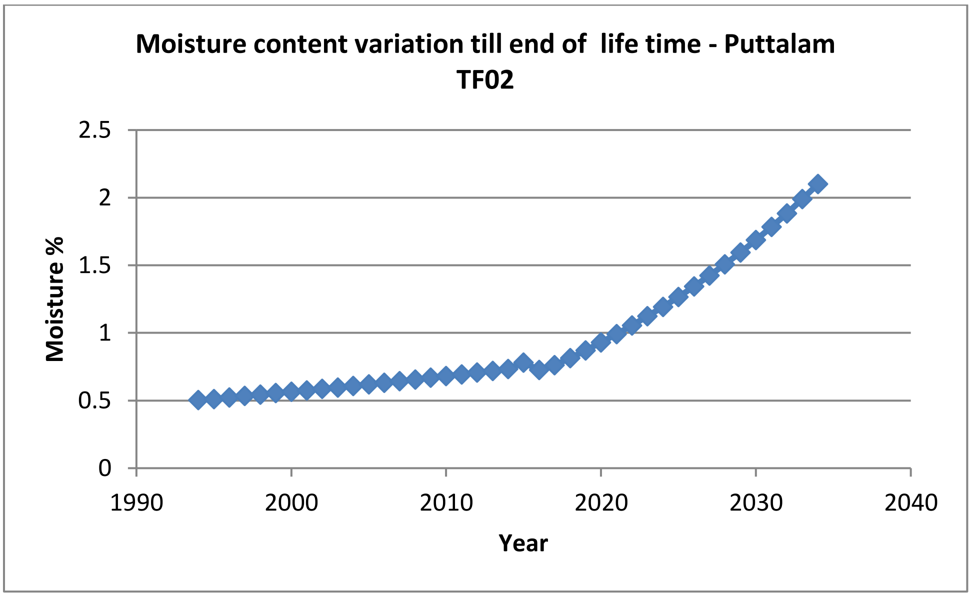




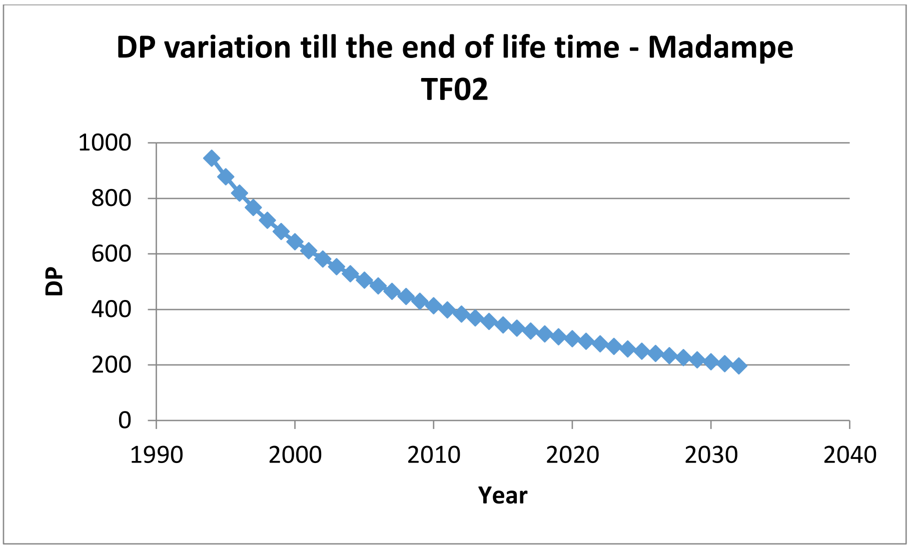
Appendix G - Moisture content variations till end of lifetime

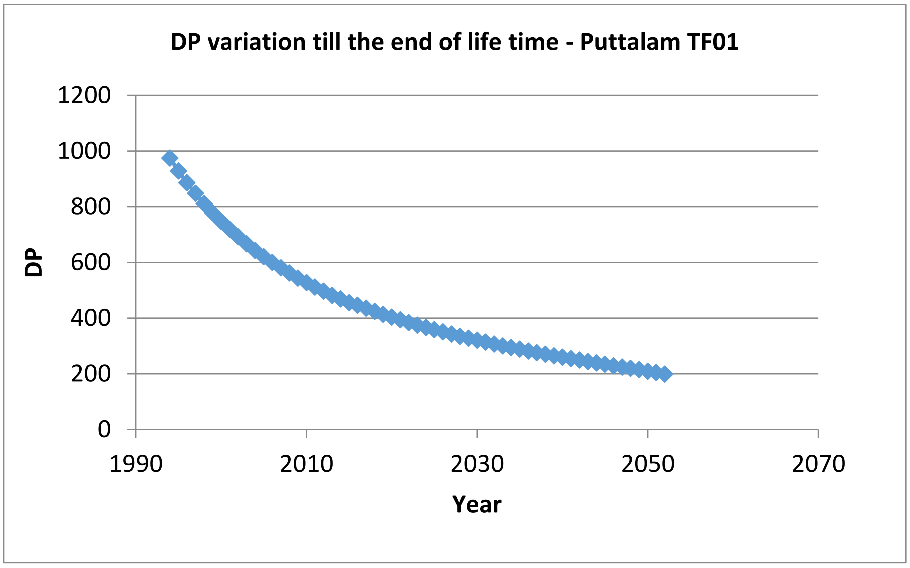


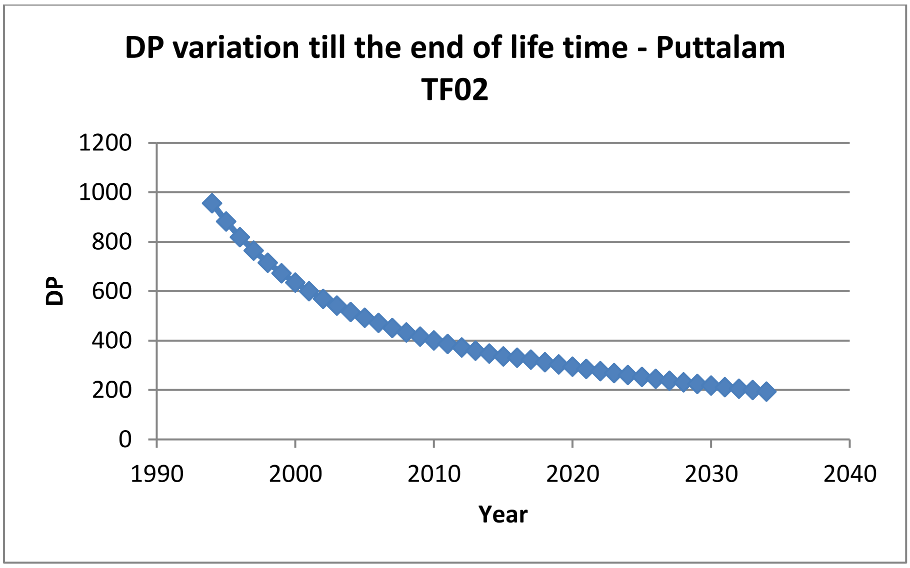




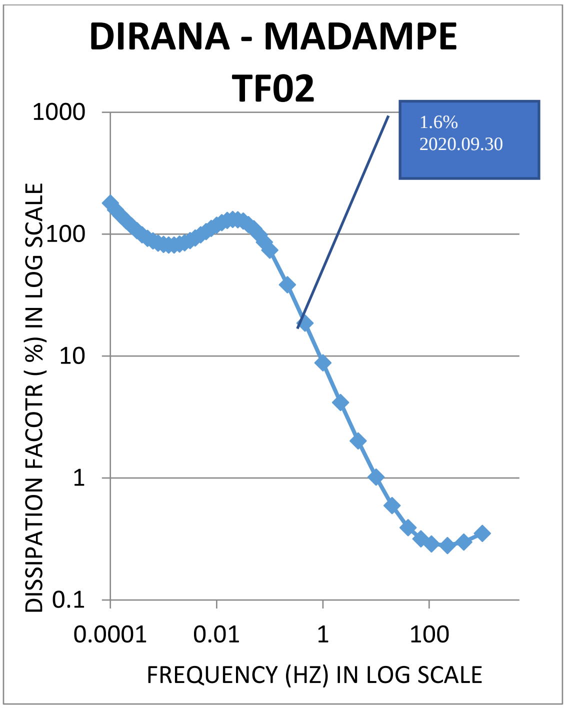
Appendix H - DP variations till end of lifetime

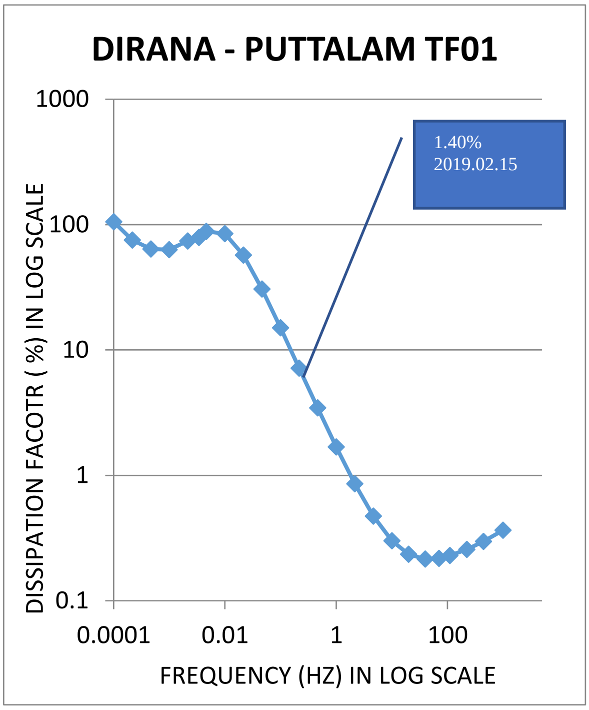


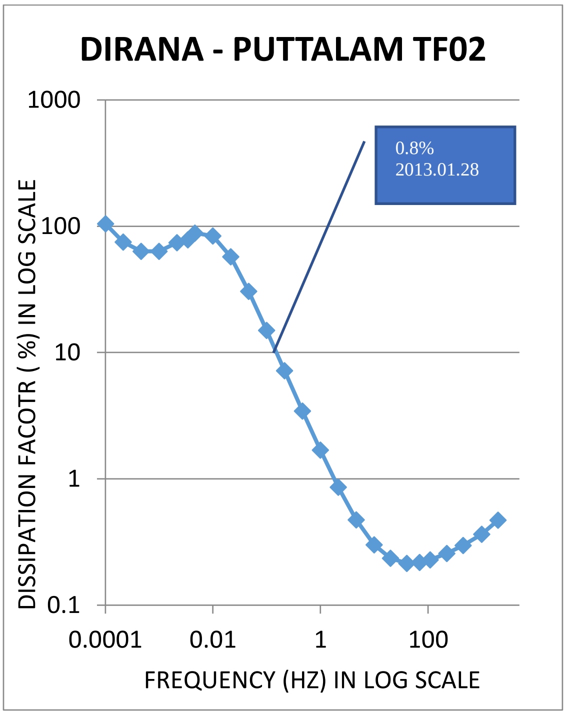




Appendix I - DIRANA measurements of all TFs







TEST CERTIFICATE

Load / Copper Loss

Subtitle		Issue date	16 October 2009		WI No.	WI-10-0601
		Version	02	Revision no. 00		

Serial No. : 3011110058	Contract /PO No. : 4200163945	Standard
Customer : Ceylon Electricity Board - Srilanka	Type : ORF 31.5/230	IEC 60076 - 1

31.5	MVA	132/ 33	kV	50	Hz	YNd1	CONN.	3	PHASE

P T Ratio	: (50-25-10-2.5)kV/√3 : 0.1kV/√3
Class	: (+/-) 0.15 ; (+/-) 1.5 Min
Brand	: MWB High Voltage System
Type	: NUZO 60 S
Serial No.	: 92 / 81015 - 92 / 81016 - 94 / 81201
Due date	: March 2013

C T Ratio	: 800-400-200-100-50-25-12.5-6.25 / 5 A
Class	
Brand	: MWB High Voltage System
Type	: VJO 605
Serial No.	: 92 / 81011 - 92 / 81012 - 92 / 81013
Due date	: March 2013

Instrument	: Power Analyzer
Brand	: Norma
Type	: 5000
Serial No.	: UO13918BA
Due date	: May, 2013

Load / Copper Loss at Temperature Measurement

PT Ratio : 50000 / 100 Volt   CT Ratio : 400 / 5.0 Amp θ_m = 32.8 °C

Tap. Pos.	VOLTAGES (kV L-N)				CURRENTS (AMP)				LOSSES (kW)			
	U_{m1}	U_{m2}	U_{m3}	U_m	I_{m1}	I_{m2}	I_{m3}	I_m	P_{m1}	P_{m2}	P_{m3}	P_m
1	8.997	9.027	9.015	9.013	125.8	124.3	124.6	124.9	35.2	29.3	46.6	111.1
				8.991				124.6				110.589
8	7.790	7.820	7.811	7.807	140.4	139.0	139.0	139.5	36.0	29.4	45.4	110.9
				7.715				137.8				108.291
18	6.401	6.422	6.417	6.413	164.0	162.7	162.4	163.0	45.2	37.5	50.1	132.8
				6.373				162.0				131.153

Load / Copper Loss Corrected to 75 °C

Tap. Pos.		1		8		18	
Temp.	(°C)	32.8	75	32.8	75	32.8	75
P_k	(kW)	110.589	120.313	108.291	119.201	131.153	146.371
$I_p^2.R_p$	(kW)	43.369	50.203	46.340	53.642	71.604	82.888
$I_s^2.R_s$	(kW)	40.995	47.455	40.995	47.455	40.995	47.455
P_{sl}	(kW)	26.225	22.655	20.956	18.103	18.554	16.028
U_r	(%)	0.351	0.382	0.344	0.378	0.416	0.465
U_x	(%)	10.670	10.670	10.117	10.117	9.829	9.829
U_k	(%)	10.676	10.677	10.123	10.124	9.838	9.840

P_k : P_m corrected to nominal tap.current

U_k : U_m corrected to nominal tap.current

K_1 : { (235 + 75) / (235 + θ_m) }

K_2 : { (235 + θ_m) / (235 + 75) }

$I_p^2.R_p$ (75 °C) : $I_p^2.R_p$ (θ_m) x K_1

$I_s^2.R_s$ (75 °C) : $I_s^2.R_s$ (θ_m) x K_1

P_{sl} (75 °C) : P_{sl} (θ_m) x K_2

Witnessed by,

Date of test : 21 May, 2012

Tested by : . .

PT. C. POWER SYSTEMS INDONESIA TEST BAY DEPARTMENT

Page . 3 - 1

TEST CERTIFICATE

Load / Copper Loss				WI No.	WI-10-0501
Subtitle		Issue date	16 October 2009		
		Version	02	Revision no.	00

Serial No. : 3011110058	Contract /PO No. : 4200163945	Standard
Customer : Ceylon Electricity Board - Srilanka	Type : ORF 31.5/230	IEC 60076 - 1

23 MVA | 132/ 33 kV | 50 Hz | YNd1 CONN. | 3 PHASE

P T Ratio	: (50-25-10-2.5)kV/√3 : 0.1kV/√3	C T Ratio	: 800-400-200-100-50-25-12.5-6.25 / 5 A
Class	: (+/-) 0.15 ; (+/-) 1.5 Min	Class	
Brand	: MWB High Voltage System	Brand	: MWB High Voltage System
Type	: NUZO 60 S	Type	: VJO 605
Serial No.	: 92 / 81015 - 92 / 81016 - 94 / 81201	Serial No.	: 92 / 81011 - 92 / 81012 - 92 / 81013
Due date	: March 2013	Due date	: March 2013

Instrument : Power Analyzer
Brand : Norma
Type : 5000
Serial No. : UO13918BA
Due date : May, 2013

Load / Copper Loss at Temperature Measurement

PT Ratio : 50000 / 100 Volt CT Ratio : 400 / 5.0 Amp θ_m = 32.5 °C

Tap. Pos.	VOLTAGES (kV L-N)				CURRENTS (AMP)				LOSSES (kW)			
	U_{m1}	U_{m2}	U_{m3}	U_m	I_{m1}	I_{m2}	I_{m3}	I_m	P_{m1}	P_{m2}	P_{m3}	P_m
1	8.997	9.027	9.015	9.013	125.8	124.3	124.6	124.9	35.2	29.3	46.6	111.1
				6.566				91.0				58.987
8	7.790	7.820	7.811	7.807	140.4	139.0	139.0	139.5	36.0	29.4	45.4	110.9
				5.632				100.6				57.715
18	6.401	6.422	6.417	6.413	164.0	162.7	162.4	163.0	45.2	37.5	50.1	132.8
				4.656				118.4				69.998

Load / Copper Loss Corrected to 75 °C

Tap. Pos.		1		8		18	
Temp.	(°C)	32.5	75	32.5	75	32.5	75
P_k	(kW)	58.987	64.201	57.715	63.566	69.998	78.162
$I_p^2.R_p$	(kW)	23.107	26.778	24.670	28.589	38.173	44.238
$I_s^2.R_s$	(kW)	21.832	25.301	21.832	25.301	21.832	25.301
P_{sl}	(kW)	14.048	12.122	11.213	9.676	9.992	8.622
U_r	(%)	0.256	0.279	0.251	0.276	0.304	0.340
U_x	(%)	7.793	7.793	7.386	7.386	7.181	7.181
U_k	(%)	7.797	7.798	7.390	7.391	7.187	7.189

P_k : P_m corrected to nominal tap.current
U_k : U_m corrected to nominal tap.current
K_1 : { (235 + 75) / (235 + θ m) }
K_2 : { (235 + θ_m) / (235 + 75) }
$I_p^2.R_p$ (75 °C) : $I_p^2.R_p$ (θ_m) x K_1
$I_s^2.R_s$ (75 °C) : $I_s^2.R_s$ (θ_m) x K_1
P_{sl} (75 °C) : P_{sl} (θ_m) x K_2

Witnessed by,

Date of test : 21 May, 2012

Tested By : ..

PT. CG POWER SYSTEMS INDONESIA
TEST BAY DEPARTMENT

TEST CERTIFICATE

Temperature Rise Test				WI No.	WI-10-1403
Subtitle	Gradient Calculation	Issue date	16 October 2009		
		Version	02 Revision no. 0		

Serial No. : 3011110058
Customer : Ceylon Electricity Board - Srilanka
Contract /PO No. : 4200163945
Type : ORF 31.5/230
Standard IEC 60076 - 2

23 MVA 132/33 kV 50 Hz YNd1 CON 3 PHASE

DESCRIPTION	23 MVA		
No-Load loss [kW]	19.8		
Load loss / copper loss [kW]	78.1		
Total loss [kW]	97.9		
Power injected [kW]	97.9		
Nominal current [A]	118.4		
Current injected [A]			
MEASUREMENT OF TEMPERATURE AT TOTAL LOSS , after the last three hours.			
- Ambient temperature [TA1]	30.9	°C	
- Top cover temperature [TC1]	76.7	°C	
- Top Radiator [TR1]	79.1	°C	
- Top Oil temperature average [TO1]	77.9	°C	
- Bottom Oil temperature [TB1]	62.1	°C	
- Average Oil temperature [AOT1]			
AOT1 = 1/2[TO1 + TB1]	70.0	°C	
- Average oil temperature rise , above cooling medium [AOTR1]			
AOTR1 = AOT1 - TA1	39.1	K	
- Top Oil Temperature Rise , above cooling medium.			
TOR = TO1 - TA1	47.0	K	
MEASUREMENT OF TEMPERATURE AT RATED CURRENT, at the time of shutdown.			
- Ambient temperature [TA2]	31.9	°C	
- Top cover temperature [TC2]	76.1	°C	
- Top Radiator [TR2]	78.0	°C	
- Top Oil temperature average [TO2]	77.1	°C	
- Bottom Oil Temperature [TB2]	61.6	°C	
- Average Oil Temperature [AOT2]			
AOT2 = 1/2[TO2 + TB2]	69.3	°C	
- Average oil temperature rise , above cooling medium [AOTR2]			
AOTR2 = AOT2 - TA2	37.5	K	
- Average Winding Temperature , by resistance [AWT]			
AWT1 , For HV winding	78.0	°C	
AWT2 , For LV winding	81.3	°C	
- Average Oil Temperature Rise Drop [during 1 hours stabilisation]			
AOTRD = AOTR1 - AOTR2	1.7	K	
- Corrected Average Winding Temperature [CAWT]			
CAWT1 , for HV winding = [AWT1 + AOTRD]	79.7	°C	
CAWT2 , for LV winding = [AWT2 + AOTRD]	83.0	°C	
- Average winding temperature rise , **above cooling medium.**			
AWTR , for HV winding = [CAWT1 - TA1]	48.9	K	
AWTR , for LV winding = [CAWT2 - TA1]	52.1	K	
- Gradient : HV winding = AWT1 - AOT2	8.7	K	
LV winding = AWT2 - AOT2	11.9	K	
- Steady state hot-spot temperature rise , above cooling medium			
HV winding = TOR + [hot-spot factor(1.3) x HV gradient]	58.4	K	
LV winding = TOR + [hot-spot factor(1.3) x LV gradient]	62.6	K	

Witnessed by,

Date of test : 22 May 2012

Tested by :

PT. CG POWER SYSTEMS INDONESIA TEST BAY DEPARTMENT

Page . 10 - 4

Appendix K FAT report of Kegalle TF

JSHP TRANSFORMER

JSHP TRANSFORMER CO., LTD

2016-110-59

5.6 Measurement of No-load Current and Loss and Excitation Current

Voltage (%)	Average Oil Temperature (℃)	Test Voltage (kV)		Test Current			No-load Loss (kW)		
		Mean	R.M.S	I_0(A)	I_0(%) Required	I_0(%) Measured	Test Loss (Pm)	Corrected Loss (P0)	Required
90	18.0	29.685	29.711	0.336	/	0.06	15.550	15.536	/
95	18.0	31.351	31.401	0.396	/	0.07	17.330	17.302	/
100(1st)	18.0	33.000	33.105	0.516	<0.2%	0.09	20.330	20.265	<22
100(2nd)	18.0	33.000	33.061	0.494		0.09	20.115	19.743	
105	18.0	34.638	34.843	0.810	/	0.15	23.740	23.599	/
110	18.0	36.298	36.920	2.113	/	0.38	29.920	29.407	/

Measuring Instrument： WT500 precision power analyzer, Manufacturer: YOKOGAWA Ltd.
Note: The first time test was performed before lightning impulse withstand test and the second time test was performed after lightning impulse withstand test.

5.7 Measurement of Short-circuit Impedance and Load Loss

【H.V.～L.V.】

Tap Position		Test Current	Test Voltage	Impedance Base:31.5MVA				Temp.:18.0℃(kW) Base:31.5MVA		Temp.:75℃(kW) Base:31.5MVA	
H.V.	L.V.	I(A)	U(kV)	Required	Tolerance	Uk(%)	Zk(Ω)	I^2R Loss	Load Loss	Required	Load Loss
1	/	67.6	8.334	/	/	10.54	71.18	77.672	103.646	/	116.372
8	/	74.0	7.056	10	±7.5%	9.95	55.05	80.154	99.122	<120	113.696
18	/	86.0	6.056	/	/	10.17	40.66	108.872	127.421	/	148.543

Measuring Instrument： WT500 precision power analyzer, Manufacturer: YOKOGAWA Ltd.

22/4/02

Cold Resistance Measurement

			T01=	15.0	℃
(**H.V.** Winding)	R1=	RBN	=	0.9361	Ω
(**L.V.** Winding)	R2=	Rbc	=	0.07525	Ω

Temperature Measurement Based on Total Loss Unit: ℃

Outlet of Radiators (Td)		Top Oil (T1)		Ambient (T02)			
3	4	1	2	5	6	7	8
33.9	34.0	57.2	57.3	17.4	17.3	17.2	17.3
34.0		57.3		17.3			

Temperature Measurement Based on Rated Current Unit: ℃

Outlet of Radiators (Td')		Top Oil (T1')		Ambient			
3	4	1	2	5	6	7	8
32.8	33.5	55.9	56.0	17.4	17.3	17.2	17.3
33.2		56.0		17.3			

Appendix L - FAT report of Kotugoda TF

ABB

TEST REPORT

No Load Losses

Report No.
VN00462

Page 5

Serial No.: VN00462

Test Condition: Final
Supplied Terminals: LA-LB-LC **Tap:** -
1st Open Terminals: HA-HB-HC-HN **Tap:** 8
2nd Open Terminals: **Tap:**
Power Base: 31.5 MVA **Rated Power:** 31.5 MVA
Average Oil Temperature: 26.8 °C

Measured Values							Losses[1] (kW)	Current	Guaranteed	
$V_{appl.}$	1.11xVmean (kV)	V_{rms} (kV)	I_A (A)	I_B (A)	I_C (A)	Losses (kW)			Losses (kW)	Current
110 %	35.75	36.26	1.290	1.074	1.015	23.16	22.83	0.2044 %		
105 %	34.50	34.75	0.6650	0.5050	0.5000	18.94	18.80	0.1010 %		
100 %	32.88	33.01	0.4190	0.2850	0.3150	15.49	15.43	0.06163 %	17.00	-
90 %	29.66	29.72	0.2950	0.1830	0.2370	11.59	11.57	0.04325 %		

Remarks: The OLTC was tested at rated voltage

[1] Corrected to Sinusoidal Wave

Test Date:	Test Engineer:	Test Department:
05-Dec-2009	Hoang Nhu Trang	PT - Test Room

ABB

TEST REPORT

Load Losses and Impedance

Report No.
VN00462

Page 7

Serial No.: VN00462

Test Condition: Final
Supplied Terminals: HA-HB-HC-HN
1st Shorted Terminals: LA-LB-LC
2nd Shorted Terminals:

Reference Temperature: 75.0 °C
Power Base: 31.5 MVA

Connection				Measured				Corrected[1]		Guaranteed	
Tap Positions			Supplied Winding V_{rated} (kV)								
Supplied	1st Shorted	2nd Shorted		Temp. (°C)	Voltage (kV)	Current (A)	Losses (kW)	Losses (kW)	Imp. (%)	Losses (kW)	Imp. (%)
1	-		145.86	28.0	15.274	124.54	109.75	120.31	10.49		
8	-		132.00	28.0	13.237	137.86	108.56	119.91	10.02	125.00	10.00
18	-		112.20	28.0	10.901	161.74	127.12	144.21	9.74		

Remarks: The OLTC was tested at rated current

[1] Corrected to Reference Temperature

Test Date:	Test Engineer:	Test Department:
05-Dec-2009	Hoang Nhu Trang	PT - Test Room

Serial No.: VN00462

Test Condition: Final ONAN
Load Case:
Cooling Condition: ONAN
Power Base: 23 MVA
Total Losses: 92.320 kW
Supplied Terminals: HA-HB-HC-HN **Tap:** 18
1st Shorted Terminals: LA-LB-LC **Tap:** -

Oil Run Results:

Measured				Corrected to Power Base	
Top Oil Temperature Rise (°C)	Mean Oil Temperature Rise (°C)	Cooling Media Temperature (°C)	Applied Losses (kW)	Top Oil Temperature Rise (°C)	Mean Oil Temperature Rise (°C)
40.6	32.6	29.8	92.600	40.4	32.5

Winding Run Results:

Terminals	Rated[1] Current (A)	Measured								Corrected[3]	
		Applied[2] Current (A)	Cold Temp. (°C)	Resistance at Cold Temp. (Ω)	Hot Resist. (Ω)	Winding Gradient (°C)	Mean Oil Temp. (°C)	Cooling Media Temp. (°C)		Final Winding Temp. Rise (°C)	Hot Spot Temp. Rise (°C)
HB-HC	118.35	118.20	26.8	1.7189	1.9913	6.8	61.5	29.8		39.3	49.3
LB-LC			26.8	0.089417	0.10337	6.3	61.5	29.8		38.8	48.6

[1] **Rated Current at Supplied Terminals at Power Base**
[2] **Applied Current at Supplied Terminals at Power Base**
[3] **Corrected to Rated Current at Power Base**

Test Date: 05-Dec-2009

Test Engineer: Hoang Nhu Trang

Test Department: PT - Test Room

Appendix M - FAT report of Maho TF

TEST CERTIFICATE

Temperature Rise Test (ONAN)				WI No.	WI-10-1403
Subtitle	Gradient Calculation	Issue date	16 October 2009		
		Version	02	Revision no.	00

Serial No. : 3011140031
Customer : Siemens Ltd/ CEB, Sri Lanka
Contract /PO No. : 42003164444
Type : ORF 31.5/230
Standard IEC 60076 - 2

23 MVA | 132/33 kV | 50 Hz | YNd1 CONN. | 3 PHASE

DESCRIPTION	23 MVA		
No-Load loss [kW]	19.6		
Load loss / copper loss [kW]	77.6		
Total loss [kW]	97.2		
Power injected [kW]	97.7		
Nominal current [A]	116.4		
Current injected [A]	116.6		
MEASUREMENT OF TEMPERATURE AT TOTAL LOSS , after the last three hours.			
- Ambient temperature [TA1]	29.4	°C	
- Top cover temperature [TC1]	68.0	°C	
- Top Radiator [TR1]	68.6	°C	
- Top Oil temperature average [TO1]	68.3	°C	
- Bottom Oil temperature [TB1]	50.8	°C	
- Average Oil temperature [AOT1] AOT1 = 1/2[TO1 + TB1]	59.6	°C	
- Average oil temperature rise , above cooling medium [AOTR1] AOTR1 = AOT1 - TA1	30.2	K	
- Top Oil Temperature Rise , above cooling medium. TOR = TO1 - TA1	38.9	K	
MEASUREMENT OF TEMPERATURE AT RATED CURRENT, at the time of shutdown.			
- Ambient temperature [TA2]	30.5	°C	
- Top cover temperature [TC2]	66.9	°C	
- Top Radiator [TR2]	67.4	°C	
- Top Oil temperature average [TO2]	67.2	°C	
- Bottom Oil Temperature [TB2]	50.6	°C	
- Average Oil Temperature [AOT2] AOT2 = 1/2[TO2 + TB2]	58.9	°C	
- Average oil temperature rise , above cooling medium [AOTR2] AOTR2 = AOT2 - TA2	28.4	K	
- Average Winding Temperature , by resistance [AWT] AWT1 , For HV winding	65.5	°C	
AWT2 , For LV winding	66.7	°C	
- Average Oil Temperature Rise Drop [during 1 hours stabilisation] AOTRD = AOTR1 - AOTR2	1.78	K	
- Corrected Average Winding Temperature [CAWT] CAWT1 , for HV winding = [AWT1 + AOTRD]	67.3	°C	
CAWT2 , for LV winding = [AWT2 + AOTRD]	68.5	°C	
- Average winding temperature rise , above cooling medium. AWTR , for HV winding = [CAWT1 - TA1]	37.9	K	
AWTR , for LV winding = [CAWT2 - TA1]	39.1	K	
- Gradient : HV winding = AWT1 - AOT2	6.6	K	
LV winding = AWT2 - AOT2	7.8	K	
- Steady state hot-spot temperature rise , above cooling medium HV winding = TOR + [hot-spot factor(1.3) x HV gradient]	47.6	K	
LV winding = TOR + [hot-spot factor(1.3) x LV gradient]	49.1	K	

Witnessed by,
1. Mrs. S.P. Pathirane - CEB
2. Mr. K S M R Sanjeewa – CEB

Date of test : 23 June, 2015
Tested by :

PT. CG POWER SYSTEMS INDONESIA TEST BAY DEPARTMENT

TEST CERTIFICATE

Load / Copper Loss

Subtitle		WI No.	WI-10-0501
Issue date	16 October 2009		
Version	02	Revision no.	00

Serial No. : 3011140031
Customer : Siemens Ltd/ CEB, Sri Lanka
Contract /PO No. : 42003164444
Type : ORF 31.5/230
Standard: IEC 60076 - 1

31.5	MVA	132/ 33	kV	50	Hz	YNd1	CONN.	3	PHASE

P T Ratio	: (50-25-10-2.5)kV/√3 : 0.1kV/√3	C T Ratio	: 800-400-200-100-50-25-12.5-6.25 / 5 A
Class	: (+/-) 0.15 ; (+/-) 1.5 Min	Class	: 0.1
Brand	: MWB High Voltage System	Brand	: MWB High Voltage System
Type	: NUZO 60 S	Type	: VJO 605
Serial No.	: 92 / 81015 - 92 / 81016 - 94 / 81201	Serial No.	: 92 / 81011 - 92 / 81012 - 92 / 81013
Due date	: March 2016	Due date	: March 2016

Instrument : Power Analyzer
Brand : Norma
Type : 5000
Serial No. : UD13918BA
Accuracy : ± 0.5%
Due date : Dec, 2015

Load / Copper Loss at Temperature Measurement (ONAF = 31.5 MVA)

PT Ratio : 50000 / 100 Volt   CT Ratio : 400 / 5.0 Amp θ_m = 31.9 °C

Tap. Pos.	VOLTAGES (kV L-N)				CURRENTS (AMP)				LOSSES (kW)			
	U_{m1}	U_{m2}	U_{m3}	U_m	I_{m1}	I_{m2}	I_{m3}	I_m	P_{m1}	P_{m2}	P_{m3}	P_m
1	8.8456	8.8657	8.8502	8.854	124.87	124.02	124.52	124.47	32.554	33.032	40.929	106.51
				8.870				124.7				106.904
8	7.5795	7.5993	7.5882	7.589	137.79	137.17	137.47	137.48	32.830	33.295	40.234	106.36
				7.607				137.8				106.856
18	6.2848	6.2989	6.2920	6.292	162.64	162.00	162.28	162.30	41.433	41.349	48.054	130.84
				6.284				162.1				130.502

Load / Copper Loss Corrected to 75 °C

Tap. Pos.		1		8		18		
Temp.	(°C)	31.9	75	31.9	75	31.9	75	P_k : P_m corrected to nominal tap.current
P_k	(kW)	106.904	116.867	106.856	117.757	130.502	145.539	U_k : U_m corrected to nominal tap.current
$I_p^2.R_p$	(kW)	42.264	49.069	45.363	52.689	70.069	81.384	K_1 : { (235 + 75) / (235 + θ m) }
$I_s^2.R_s$	(kW)	40.347	46.862	40.347	46.862	40.347	46.862	K_2 : { (235 + θ_m) / (235 + 75) }
P_{st}	(kW)	24.293	20.916	21.146	18.206	20.086	17.293	$I_p^2.R_p$ (75 °C) : $I_p^2.R_p$ (θ_m) x K_1
U_r	(%)	0.339	0.371	0.339	0.374	0.414	0.462	$I_s^2.R_s$ (75 °C) : $I_s^2.R_s$ (θ_m) x K_1
U_x	(%)	10.528	10.528	9.975	9.975	9.691	9.691	P_{st} (75 °C) : P_{st} (θ_m) x K_2
U_k	(%)	10.533	10.534	9.981	9.982	9.700	9.703	

Witnessed by

1. Mrs. S.P. Pathirane - CEB

2. Mr. K S M R Sanjeewa – CEB

Date of test : 22 June, 2015

Tested by : ....

PT. CG POWER SYSTEMS INDONESIA
TEST BAY DEPARTMENT

TEST CERTIFICATE

Load / Copper Loss				WI No.	WI-10-0601
Subtitle	Issue date	16 October 2009			
	Version	02	Revision no. 00		

Serial No. : 3011140031 — Contract /PO No. : 42003164444 — Standard IEC 60076 - 1

Customer : Siemens Ltd/ CEB, Sri Lanka — Type : ORF 31.5/230

23	MVA	132/ 33	kV	50	Hz	YNd1	CONN.	3	PHASE

P T Ratio	: (50-25-10-2.5)kV/√3 : 0.1kV/√3	C T Ratio	: 800-400-200-100-50-25-12.5-6.25 / 5 A
Class	: (+/-) 0.15 ; (+/-) 1.5 Min	Class	: 0.1
Brand	: MWB High Voltage System	Brand	: MWB High Voltage System
Type	: NUZO 60 S	Type	: VJO 605
Serial No.	: 92 / 81015 - 92 / 81016 - 94 / 81201	Serial No.	: 92 / 81011 - 92 / 81012 - 92 / 81013
Due date	: March 2016	Due date	: March 2016

Instrument	: Power Analyzer
Brand	: Norma
Type	: 5000
Serial No.	: UO139188A
Accuracy	: ± 0.5%
Due date	: Dec, 2015

Load / Copper Loss at Temperature Measurement (ONAN = 23 MVA)

PT Ratio : 50000 / 100 Volt — CT Ratio : 400 / 5.0 Amp — θ_m = 31.9 °C

Tap. Pos.	VOLTAGES (kV L-N)				CURRENTS (AMP)				LOSSES (kW)			
	U_{m1}	U_{m2}	U_{m3}	U_m	I_{m1}	I_{m2}	I_{m3}	I_m	P_{m1}	P_{m2}	P_{m3}	P_m
1	8.8456	8.8657	8.8502	8.854	124.87	124.02	124.52	124.47	32.554	33.032	40.929	106.51
				6.477				91.1				56.994
8	7.5795	7.5993	7.5882	7.589	137.79	137.17	137.47	137.48	32.830	33.296	40.234	106.36
				5.554				100.6				58.968
18	6.2848	6.2989	6.2920	6.292	162.64	162.00	162.28	162.30	41.433	41.349	48.054	130.84
				4.588				118.4				69.575

Load / Copper Loss Corrected to 75 °C

Tap. Pos.		1		8		18		
Temp.	(°C)	31.9	75	31.9	75	31.9	75	P_k : P_m corrected to nominal tap.current
P_k	(kW)	56.994	62.305	56.968	62.780	69.575	77.592	U_k : U_m corrected to nominal tap.current
$I_p^2.R_p$	(kW)	22.532	26.171	24.186	28.090	37.356	43.388	K_1 : { (235 + 75) / (235 + θ m) }
$I_s^2.R_s$	(kW)	21.510	24.984	21.510	24.984	21.510	24.984	K_2 : { (235 + θ_m) / (235 + 75) }
P_{st}	(kW)	12.951	11.151	11.273	9.706	10.709	9.220	$I_p^2.R_p$ (75 °C) : $I_p^2.R_p$ (θ_m) x K_1
U_r	(%)	0.248	0.271	0.248	0.273	0.302	0.337	$I_s^2.R_s$ (75 °C) : $I_s^2.R_s$ (θ_m) x K_1
U_x	(%)	7.687	7.687	7.284	7.284	7.076	7.076	P_{st} (75 °C) : P_{st} (θ_m) x K_2
U_k	(%)	7.691	7.692	7.288	7.289	7.083	7.084	

Witnessed by

1. Mrs. S.P. Pathirane - CEB

2. Mr. K S M R Sanjeewa – CEB

Date of test : 22 June, 2015

Tested by :

PT. CG POWER SYSTEMS INDONESIA — TEST BAY DEPARTMENT

Page 3 - 2

TEST CERTIFICATE

No-Load / Core Loss			W/ No.	WI-10-0601
Subtitle	Issue date	16 October 2009		
	Version	02	Revision no.	00

Serial No. : 3011140031
Customer : Siemens Ltd/ CEB, Sri Lanka
Contract /PO No. : 42003164444
Type : ORF 31.5/230
Standard IEC 60076 - 1

31.5	MVA	132/ 33	kV	50	Hz	YNd1	CONN.	3	PHASE

P T Ratio	: (50-25-10-2.5)kV/√3 : 0.1kV/√3	C T Ratio	: 800-400-200-100-50-25-12.5-6.25 / 5 A
Class	: (+/-) 0.15 ; (+/-) 1.5 Min	Class	: 0.1
Brand	: MWB High Voltage System	Brand	: MWB High Voltage System
Type	: NUZO 60 S	Type	: VJO 605
Serial No.	: 92 / 81015 - 92 / 81016 - 94 / 81201	Serial No.	: 92 / 81011 - 92 / 81012 - 92 / 81013
Due date	: March 2016	Due date	: March 2016

Instrument	: Power Analyzer
Brand	: Norma
Type	: 5000
Serial No.	: UD138188A
Accuracy	: ± 0.3%
Due date	: Dec, 2015

PT Ratio : 50000 / 100 Volt CT Ratio : 50 / 5 Amp

Vavg		VOLTAGES (kV mean)			CURRENTS (Amp)			LOSSES (kW)			VOLTAGES (kV rms)		
(%)	Phase	2r - 2n	2y-2n	2b-2n	I1	I2	I3	P1	P2	P3	2r - 2n	2y-2n	2b-2n
90	Meas.	17.129	17.161	17.137	0.2442	0.2854	0.3764	3.7605	4.6634	6.2482	17.125	17.150	17.122
			Average =	17.142		Average =	0.3020		P measured =	14.672		Average =	17.132
100	Meas.	19.033	19.076	19.046	0.3724	0.3776	0.5253	4.8206	6.2736	8.4699	19.022	19.053	19.019
			Average =	19.052		Average =	0.4251		P measured =	19.564		Average =	19.031
110	Meas.	20.930	20.976	20.938	1.6700	1.6421	2.0876	3.368	12.550	12.022	20.847	20.878	20.817
			Average =	20.948		Average =	1.8002		P measured =	27.940		Average =	20.847

Correction : Po = P meas. (1+d) Where : d = (kV mean-kV r.m.s) / kV mean

Po = 19.585 kW (at 100 %)

Witnessed by,

1. Mrs. S.P. Pathirane - CEB

2. Mr. K S M R Sanjeewa – CEB

Date of test : 22 June, 2015

Tested by : ....

PT POWER SYSTEMS INDONESIA
TEST BAY DEPARTMENT

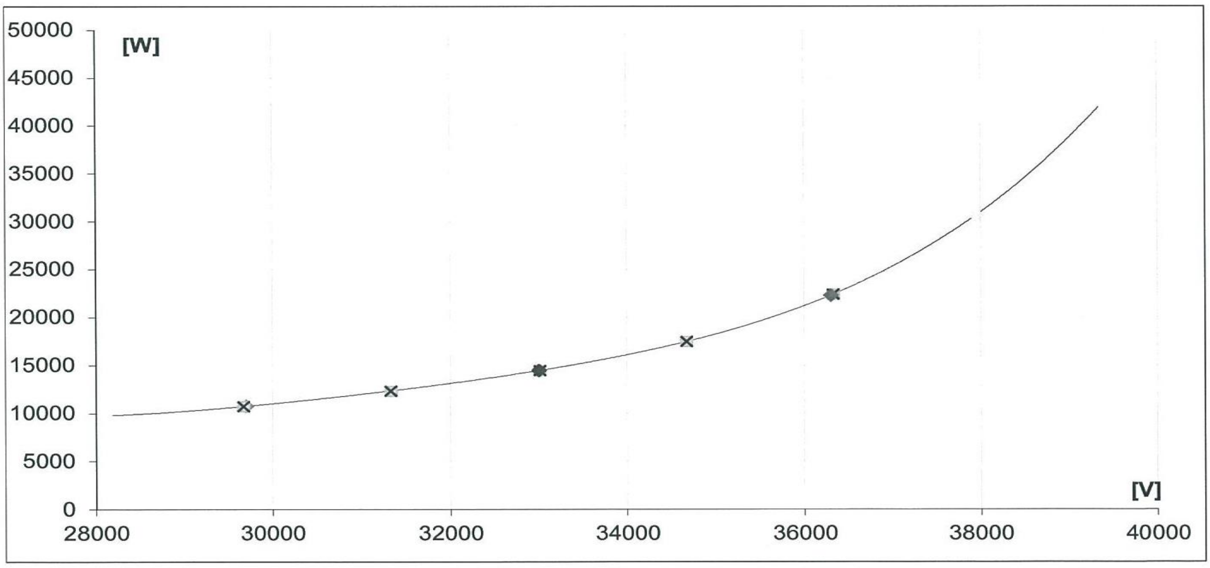
Appendix N - FAT report of Kiribathkumbura TF

Transformer		N°	:	150631A/02				
Power		[MVA]	:	23,000	ONAN	/ 31,500		ONAF
Voltage	HV	[kV]	:	132,000	+ 3 - 9 x	1,670%		
Voltage	MV	[kV]	:	33,000	-	-		

Measurement of no-load loss and current. (ONAF: 31,5 MVA)

Voltage average value				Losses			
V uv [V]	V vw [V]	V wu [V]	Average [V]	W u [W]	W v [W]	W w [W]	Total [W]
36283	36457	36248	36329	9560	2365	10460	22385
34607	34765	34639	34670	7366	2949	7140	17455
32998	33067	32969	33011	6160	2834	5465	14459
31300	31363	31318	31327	5230	2606	4501	12337
29620	29717	29666	29668	4519	2369	3831	10719

		Measured	Guaranted	
No-Load Losses at	**Vn [W]:**	**14442**	**15500**	**+ 0 %**
No-Load Losses at	0,90 Vn [W]:	10746	-	-
No-Load Losses at	1,10 Vn [W]:	22273	-	-



Result : SATISFACTORY.

Date 30/12/15 Customer

Restricted

Siemens Transformers S.p.A. Testing Service

Transformer		N°	: 150631A/02		
Power		[MVA]	: 23,000	ONAN /	31,500 ONAF
Voltage	HV	[kV]	: 132,000	+ 3 - 9 x	1,670%
Voltage	MV	[kV]	: 33,000	-	-
Voltage	(D)	[kV]	: -	-	-

Summary of guaranteed and measured values

Measurement of no-load loss and current. — ONAF: 31,5 MVA

		Guaranted	Tolerances (IEC)	Measured	[%]
Losses	Vn [W]	15500	+ 0 %	**14442**	-6,82%
Losses	0,90 Vn [W]	-	-	**10746**	-
Losses	1,10 Vn [W]	-	-	**22273**	-
Current	Vn [%]	0,22%	+ 30 %	**0,068%**	-68,9%
Current	0,90 Vn [%]	0,20%	+ 30 %	**0,044%**	-78,2%
Current	1,10 Vn [%]	0,70%	+ 30 %	**0,218%**	-68,8%
Guaranted	1,20 Vn [%]	4,00%	+ 30 %	**1,021%**	-74,5%

Measurement of short-circuit impedance and load loss. — ONAN: 23 MVA

T.C. Position			Guaranted	Tolerances (IEC)	Measured	[%]
4	132,000 kV	Losses [W]	-	-	**74721**	-
		Short circuit impedance [%]	8,05	± 10 %	**8,02**	-0,43%
		Total Losses [W]	-	-	**89164**	-
1	138,613 kV	Losses [W]	-	-	**74236**	-
		Short circuit impedance [%]	8,27	± 15 %	**8,24**	-0,41%
		Total Losses [W]	-	-	**88678**	-
13	112,160 kV	Losses [W]	-	-	**77716**	-
		Short circuit impedance [%]	7,53	± 15 %	**7,53**	-0,02%
		Total Losses [W]	-	-	**92159**	-

Measurement of short-circuit impedance and load loss. — ONAF: 31,5 MVA

T.C. Position			Guaranted	Tolerances (IEC)	Measured	[%]
4	132,000 kV	Losses [W]	145000	+ 0 %	**140155**	-3,34%
		Short circuit impedance [%]	11,02	± 7,5 %	**10,98**	-0,39%
		Total Losses [W]	160500	+ 0 %	**154598**	-3,68%
1	138,613 kV	Losses [W]	-	-	**139245**	-
		Short circuit impedance [%]	11,33	± 10 %	**11,28**	-0,44%
		Total Losses [W]	-	-	**153687**	-
13	112,160 kV	Losses [W]	-	-	**145774**	-
		Short circuit impedance [%]	10,31	± 10 %	**10,31**	0,01%
		Total Losses [W]	-	-	**160216**	-

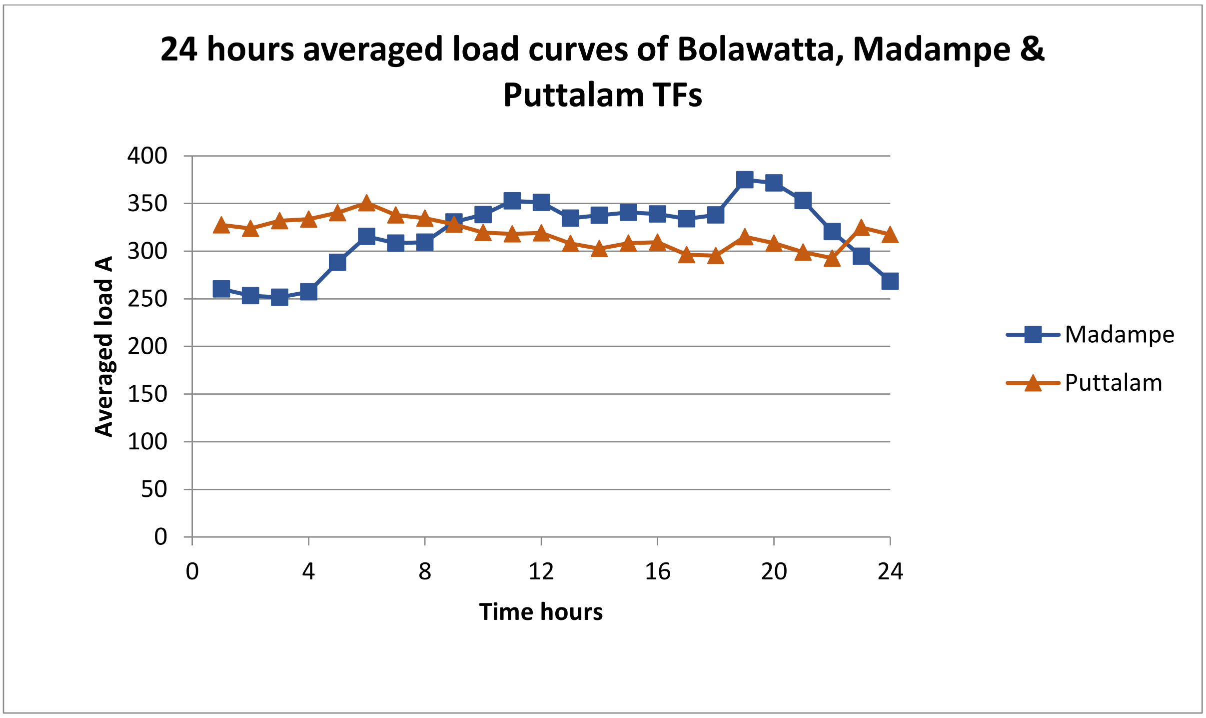
Date 29 ÷ 31/12/15

Siemens Transformers S.p.A.
Testing Service

Customer

Restricted

Appendix O - Average 24-hour Load curves of Madampe & Puttalam TFs



Appendix P – Thermal Model Code

```
import math
from openpyxl import Workbook

#Inputs
exp = math.e
alarm = 90
amb = 28

#TF Nameplate Data Inputs
delta_To_rated = 40.075
delta_H_AM_rated = 53.433
delta_H_rated = delta_H_AM_rated-delta_To_rated
No_load_loss = 18.634
Load_loss_ONAN = 63.173
Load_loss_FG2 = 117.641
Load_loss_FG1 = Load_loss_ONAN + (Load_loss_FG2-Load_loss_ONAN)/2
C_ONAN = 12443.6
C_FG1 = C_FG2 = 15935.9

TW = 8/60
n_ONAN = 0.8
n_FG1 = n_FG2 = 0.8
m_ONAN =  0.8
m_FG1 = m_FG2 = 0.8
I_ONAN = 402.4074
I_FG1 = 483.029
I_FG2 = 551.123

R_ONAN = Load_loss_ONAN/No_load_loss
R_FG1 = Load_loss_FG1/No_load_loss
R_FG2 = Load_loss_FG2/No_load_loss

ki_ONAN = 332 /I_ONAN
ki_FG1 = 332 / I_FG1
ki_FG2 = 332 / I_FG2


#temp_ki_ONAN = 0

load = [260, 253, 252, 257, 288, 315, 308, 309, 331, 338, 353, 351, 335, 338, 341,
339, 334, 338, 375, 372, 353, 321, 295, 269 ]
max_load = max(load)
max_load_tf = 550
max_load_percentage = []
percentage = []
```

```
def getKiInitValue(condition):
    if condition==0:
        return ki_ONAN
    elif condition==1:
        return ki_FG1
    else:
        return ki_FG2

temp_ki=0

#KI = 0

kulist=[]
# 0 = ONAN , 1 = FG1 , 2 = FG2
def hotspot_temp(indexVal,load,condition,initConditionCall):

    ku_ONAN = load/I_ONAN
    ku_FG1 = load/I_FG1
    ku_FG2 = load/I_FG2

    if initConditionCall==True and condition==0:
        temp_ki = ki_ONAN
    elif initConditionCall==True and condition==1:
        temp_ki = ki_FG1
    elif initConditionCall==True and condition==2:
        temp_ki = ki_FG2
    else:
        temp_ki = getKiInitValue(condition) if indexVal == 0 else kulist[indexVal-1]


    delta_To_i = 0
    delta_To_u = 0
    Tto_rated = 0
    Tto = 0
    Delta_To_Final= 0
    delta_H_i = 0
    delta_H_u = 0
    Delta_H_Final = 0
    hotspot_final =0

    if condition == 0 :
        delta_To_i = delta_To_rated * ((temp_ki**2 * R_ONAN +1)/(R_ONAN+1))**n_ONAN
        delta_To_u = delta_To_rated * ((ku_ONAN**2 * R_ONAN +1)/(R_ONAN+1))**n_ONAN

        Tto_rated = C_ONAN*delta_To_rated/(Load_loss_ONAN*1000)

        Tto = Tto_rated * ((delta_To_u/delta_To_rated)-
(delta_To_i/delta_To_rated))/((delta_To_u/delta_To_rated)**(1/n_ONAN)-
(delta_To_i/delta_To_rated)**(1/n_ONAN))
```

```
        Delta_To_Final = (delta_To_u - delta_To_i)*(1-exp**(-1/Tto))+delta_To_i

        delta_H_i = delta_H_rated * temp_ki **(2*m_ONAN)
        delta_H_u = delta_H_rated * ku_ONAN **(2*m_ONAN)

        Delta_H_Final = (delta_H_u-delta_H_i)*(1-exp**(-1/TW))+delta_H_i

        hotspot_final = Delta_H_Final + Delta_To_Final + amb

        if initConditionCall == False:
            kulist.append(ku_ONAN)
        #kulist[indexVal]=ku_ONAN

#Fan Group 1
    elif condition == 1 :
        delta_To_i = delta_To_rated * ((temp_ki**2 * R_FG1 +1)/(R_FG1+1))**n_FG1
        delta_To_u = delta_To_rated * ((ku_FG1**2 * R_FG1 +1)/(R_FG1+1))**n_FG1

        Tto_rated = C_FG1*delta_To_rated/(Load_loss_FG1*1000)

        Tto = Tto_rated * ((delta_To_u/delta_To_rated)-
(delta_To_i/delta_To_rated))/((delta_To_u/delta_To_rated)**(1/n_FG1)-
(delta_To_i/delta_To_rated)**(1/n_FG1))

        Delta_To_Final = (delta_To_u - delta_To_i)*(1-exp**(-1/Tto))+delta_To_i

        delta_H_i = delta_H_rated * temp_ki **(2*m_FG1)
        delta_H_u = delta_H_rated * ku_FG1 **(2*m_FG1)

        Delta_H_Final = (delta_H_u-delta_H_i)*(1-exp**(-1/TW))+delta_H_i

        hotspot_final = Delta_H_Final + Delta_To_Final + amb

        if initConditionCall == False:
            kulist.append(ku_FG1)
        #kulist[indexVal]=ku_FG1


# Fan Group 2
    elif condition == 2 :
        delta_To_i = delta_To_rated * ((temp_ki**2 * R_FG2 +1)/(R_FG2+1))**n_FG2
        delta_To_u = delta_To_rated * ((ku_FG2**2 * R_FG2 +1)/(R_FG2+1))**n_FG2

        Tto_rated = C_FG2*delta_To_rated/(Load_loss_FG2*1000)

        Tto = Tto_rated * ((delta_To_u/delta_To_rated)-
(delta_To_i/delta_To_rated))/((delta_To_u/delta_To_rated)**(1/n_FG2)-
(delta_To_i/delta_To_rated)**(1/n_FG2))
```

```
        Delta_To_Final = (delta_To_u - delta_To_i)*(1-exp**(-1/Tto))+delta_To_i

        delta_H_i = delta_H_rated * temp_ki **(2*m_FG2)
        delta_H_u = delta_H_rated * ku_FG2 **(2*m_FG2)

        Delta_H_Final = (delta_H_u-delta_H_i)*(1-exp**(-1/TW))+delta_H_i

        hotspot_final = Delta_H_Final + Delta_To_Final + amb

        if initConditionCall == False:
            kulist.append(ku_FG2)
        #kulist[indexVal]=ku_FG2

    hotspot_final = hotspot_final * 1

    return hotspot_final


currentLoad=[]

# Function to check the initial hour condition, whether ONAN, FG1 or FG2 based on
temp setting
def getInitialCondition(fg1,fg2,firstHourLoad):
    condition_val = 0

    intial_Hotspot_ONAN= hotspot_temp(0,firstHourLoad,0,True)
    intial_Hotspot_FG1= hotspot_temp(0,firstHourLoad,1,True)

    if intial_Hotspot_ONAN >= fg1 :
        if intial_Hotspot_FG1 >= fg2 :
            condition_val = 2
        else :
            condition_val = 1

    else:
        condition_val = 0

    return condition_val


#Function to get numbers of hours that fans operated
def runtime_count(condition, counters):
    if condition == 0:
        counters["runtime_ONAN"] += 1
    elif condition == 1:
        counters["runtime_FG1"] += 1
    elif condition == 2:
        counters["runtime_FG2"] += 1
```

```
# Initialize counters
counters = {
    "runtime_ONAN": 0,
    "runtime_FG1": 0,
    "runtime_FG2": 0
}

# Function to get all the percentage values that can be used for iteration
def get_load_percentage_list():
    max_load_percentage.append(max_load)
    z = 1
    index = 0

    while max_load_percentage[index] < max_load_tf :
        #print(z, max_load_percentage[index])
        percentage.append(z)
        z += 0.05
        max_load_percentage.append(max_load*z)

        index += 1

get_load_percentage_list()

#Function to get New loads after multiplication from Percentages
def getLoad(index):
    newLoadList=[]
    for i in range(len(load)):
        newLoadList.append(load[i]*percentage[index])

    return newLoadList


init_condition_value = 0
hotspot_temp_value = 0
hotspot_temp_value_list=[]
ONAN_time_List=[]
FG1_time_List=[]
FG2_time_List=[]

TF_workbook = Workbook()
sheet1 = TF_workbook.active
sheet1.title = "Thermal Model"


sheet2 = TF_workbook.create_sheet("Summary")


print_count = 0
```

```
count=0

for temp_fg1 in range (amb,alarm-5, 4):

            for temp_fg2 in range (temp_fg1, alarm, 4):
                for j in range (len(percentage)):
                    currentLoad=getLoad(j)
                    #print(currentLoad)
                    hotspot_temp_value=0
                    hotspot_temp_value_list=[]
                    lifeTime_list=[]

                    for i in range (len(currentLoad)):

                        if hotspot_temp_value < 91 :

                            init_condition_value = 0
                            init_condition_value=getInitialCondition(temp_fg1,temp_
fg2,currentLoad[0])
                            if i==0:

                                hotspot_temp_value =
hotspot_temp(i,currentLoad[i],init_condition_value,False)
                                runtime_count(init_condition_value,counters)

                            elif i == 1 :
                                hotspot_temp_value =
hotspot_temp(i,currentLoad[i],init_condition_value,False)
                                runtime_count(init_condition_value,counters)
                            else :

                                if hotspot_temp_value < temp_fg1 :
                                    hotspot_temp_value =
hotspot_temp(i,currentLoad[i],0,False)
                                    runtime_count(0,counters)

                                elif hotspot_temp_value >= temp_fg1 and
hotspot_temp_value < temp_fg2 :
                                    hotspot_temp_value =
hotspot_temp(i,currentLoad[i],1,False)
                                    runtime_count(1,counters)

                                elif hotspot_temp_value >= temp_fg2 :
                                    hotspot_temp_value =
hotspot_temp(i,currentLoad[i],2,False)
                                    runtime_count(2,counters)
```

```
                        lifeTime_list.append({"ONAN":
counters["runtime_ONAN"],"FG1": counters["runtime_FG1"],"FG2":
counters["runtime_FG2"]})

                        hotspot_temp_value_list.append(hotspot_temp_value)


                    elif hotspot_temp_value >= 91 :
                        break

                    #print("hotspot value list
len:",len(hotspot_temp_value_list))

                    if len(hotspot_temp_value_list) ==24:
                        for m in range(len(hotspot_temp_value_list)):
                            lifetime_element = lifeTime_list[m]

                            print(temp_fg1,temp_fg2,currentLoad[i],hotspot_temp
_value_list[m],lifetime_element["ONAN"],lifetime_element["FG1"],lifetime_element["F
G2"])
                            print_count += 1

                            value1 = temp_fg1
                            value2 = temp_fg2
                            value3 = currentLoad[m]
                            value4 = hotspot_temp_value_list[m]

                            sheet1.cell(row=1, column=1, value='Temp_fG1')
                            sheet1.cell(row=1, column=2, value='Temp_FG2')
                            sheet1.cell(row=1, column=3, value='Increased %')
                            sheet1.cell(row=1, column=4, value='Initial Load')
                            sheet1.cell(row=1, column=5, value='Increased
Load')

                            sheet1.cell(row=1, column=6, value='Hotspot Temp')
                            sheet1.cell(row=1, column=7, value='Runtime
Hours_ONAN')
                            sheet1.cell(row=1, column=8, value='Runtime
Hours_FG1')
                            sheet1.cell(row=1, column=9, value='Runtime
Hours_FG2')
                            sheet1.cell(row=count + 2, column=1, value=value1)
                            sheet1.cell(row=count + 2, column=2, value=value2)
                            sheet1.cell(row=count + 2, column=3, value=
100*(percentage[j]-1))
                            sheet1.cell(row=count+ 2, column=4, value=load[m])
                            sheet1.cell(row=count+ 2, column=5, value=value3)
                            sheet1.cell(row=count + 2, column=6, value=value4)
```

```
                                sheet1.cell(row=count + 2, column=7, value=
lifetime_element["ONAN"])
                                sheet1.cell(row=count+ 2, column=8,
value=lifetime_element["FG1"])
                               sheet1.cell(row=count + 2, column=9,
value=lifetime_element["FG2"])

                                count +=1

                    kulist=[]
                    counters = {
                        "runtime_ONAN": 0,
                        "runtime_FG1": 0,
                        "runtime_FG2": 0
                    }

print("print count:", print_count)
print("count",count)

print ("new number of rows are :",sheet1.max_row-1 )

TF_workbook.save('example.xlsx')
```

Appendix Q – Thermal Model Results – Madampe TF 2

Temp_FG1	Temp_FG2	Increased Load %	Initial Load	Increased Load	Hotspot Temp	Runtime Hours_ONAN	Runtime Hours_FG1	Runtime Hours_FG2
32	44	0	260	260	52.3588	0	0	1
32	44	0	253	253	48.23712	0	0	2
32	44	0	252	252	47.86191	0	0	3
32	44	0	257	257	47.98439	0	0	4
32	44	0	288	288	49.33748	0	0	5
32	44	0	315	315	51.95525	0	0	6
32	44	0	308	308	53.15492	0	0	7
32	44	0	309	309	52.80282	0	0	8
32	44	0	331	331	53.74217	0	0	9
32	44	0	338	338	55.28462	0	0	10
32	44	0	353	353	56.33164	0	0	11
32	44	0	351	351	57.1442	0	0	12
32	44	0	335	335	56.34744	0	0	13
32	44	0	338	338	55.51847	0	0	14
32	44	0	341	341	55.82081	0	0	15
32	44	0	339	339	55.91456	0	0	16
32	44	0	334	334	55.58779	0	0	17
32	44	0	338	338	55.45983	0	0	18
32	44	0	375	375	57.30078	0	0	19
32	44	0	372	372	59.42825	0	0	20
32	44	0	353	353	58.40468	0	0	21
32	44	0	321	321	55.89627	0	0	22
32	44	0	295	295	52.99445	0	0	23

32	44	0	269	269	50.59804	0	0	24
32	44	5	260	273	52.81732	0	0	1
32	44	5	253	265.65	49.32624	0	0	2
32	44	5	252	264.6	48.91819	0	0	3
32	44	5	257	269.85	49.05129	0	0	4
32	44	5	288	302.4	50.52231	0	0	5
32	44	5	315	330.75	53.3677	0	0	6
32	44	5	308	323.4	54.66958	0	0	7
32	44	5	309	324.45	54.28756	0	0	8
32	44	5	331	347.55	55.30875	0	0	9
32	44	5	338	354.9	56.98281	0	0	10
32	44	5	353	370.65	58.12005	0	0	11
32	44	5	351	368.55	59.00058	0	0	12
32	44	5	335	351.75	58.13467	0	0	13
32	44	5	338	354.9	57.2364	0	0	14
32	44	5	341	358.05	57.56461	0	0	15
32	44	5	339	355.95	57.66598	0	0	16
32	44	5	334	350.7	57.31105	0	0	17
32	44	5	338	354.9	57.17282	0	0	18
32	44	5	375	393.75	59.17389	0	0	19
32	44	5	372	390.6	61.47883	0	0	20
32	44	5	353	370.65	60.36661	0	0	21
32	44	5	321	337.05	57.64371	0	0	22
32	44	5	295	309.75	54.49436	0	0	23
32	44	5	269	282.45	51.8918	0	0	24
32	44	10	260	286	53.29162	0	0	1
32	44	10	253	278.3	50.45287	0	0	2

32	44	10	252	277.2	50.01104	0	0	3
32	44	10	257	282.7	50.15516	0	0	4
32	44	10	288	316.8	51.74809	0	0	5
32	44	10	315	346.5	54.82802	0	0	6
32	44	10	308	338.8	56.23458	0	0	7
32	44	10	309	339.9	55.82189	0	0	8
32	44	10	331	364.1	56.92777	0	0	9
32	44	10	338	371.8	58.73708	0	0	10
32	44	10	353	388.3	59.96738	0	0	11
32	44	10	351	386.1	60.91752	0	0	12
32	44	10	335	368.5	59.98012	0	0	13
32	44	10	338	371.8	59.01091	0	0	14
32	44	10	341	375.1	59.36575	0	0	15
32	44	10	339	372.9	59.47488	0	0	16
32	44	10	334	367.4	59.0909	0	0	17
32	44	10	338	371.8	58.94225	0	0	18
32	44	10	375	412.5	61.10891	0	0	19
32	44	10	372	409.2	63.59566	0	0	20
32	44	10	353	388.3	62.39182	0	0	21
32	44	10	321	353.1	59.44786	0	0	22
32	44	10	295	324.5	56.04383	0	0	23
32	44	10	269	295.9	53.22899	0	0	24
32	44	15	260	299	53.78149	0	0	1
32	44	15	253	290.95	51.61617	0	0	2
32	44	15	252	289.8	51.13967	0	0	3
32	44	15	257	295.55	51.2952	0	0	4
32	44	15	288	331.2	53.01398	0	0	5

32	44	15	315	362.25	56.33519	0	0	6
32	44	15	308	354.2	57.84879	0	0	7
32	44	15	309	355.35	57.40472	0	0	8
32	44	15	331	380.65	58.59809	0	0	9
32	44	15	338	388.7	60.54618	0	0	10
32	44	15	353	405.95	61.87235	0	0	11
32	44	15	351	403.65	62.89367	0	0	12
32	44	15	335	385.25	61.88247	0	0	13
32	44	15	338	388.7	60.84074	0	0	14
32	44	15	341	392.15	61.22296	0	0	15
32	44	15	339	389.85	61.33995	0	0	16
32	44	15	334	384.1	60.92604	0	0	17
32	44	15	338	388.7	60.76689	0	0	18
32	44	15	375	431.25	63.10454	0	0	19
32	44	15	372	427.8	65.77726	0	0	20
32	44	15	353	405.95	64.47886	0	0	21
32	44	15	321	369.15	61.30742	0	0	22
32	44	15	295	339.25	57.6417	0	0	23
32	44	15	269	309.35	54.6086	0	0	24
32	44	20	260	312	54.28678	0	0	1
32	44	20	253	303.6	52.81537	0	0	2
32	44	20	252	302.4	52.30332	0	0	3
32	44	20	257	308.4	52.47066	0	0	4
32	44	20	288	345.6	54.31916	0	0	5
32	44	20	315	378	57.88825	0	0	6
32	44	20	308	369.6	59.51115	0	0	7
32	44	20	309	370.8	59.03502	0	0	8

32	44	20	331	397.2	60.31865	0	0	9
32	44	20	338	405.6	62.40896	0	0	10
32	44	20	353	423.6	63.83373	0	0	11
32	44	20	351	421.2	64.92777	0	0	12
32	44	20	335	402	63.8405	0	0	13
32	44	20	338	405.6	62.72472	0	0	14
32	44	20	341	409.2	63.13505	0	0	15
32	44	20	339	406.8	63.26001	0	0	16
32	44	20	334	400.8	62.8153	0	0	17
32	44	20	338	405.6	62.64556	0	0	18
32	44	20	375	450	65.15952	0	0	19
32	44	20	372	446.4	68.02225	0	0	20
32	44	20	353	423.6	66.62641	0	0	21
32	44	20	321	385.2	63.22115	0	0	22
32	44	20	295	354	59.28693	0	0	23
32	44	20	269	322.8	56.02971	0	0	24

This will continue until the iterations are over by the set conditions.

Appendix R – Transformer Life Estimation Model Code

```
import math
import openpyxl

# Load an existing Excel file
workbook_moist = openpyxl.load_workbook('Moisture_Data_Input.xlsx')
sheet = workbook_moist.active

# Load an hotspot values Excel file
TF_workbook = openpyxl.load_workbook('example.xlsx')
sheet1 = TF_workbook.active

#Inputs
Oil_weigt = 16500
#in kg
paper_weight = Oil_weigt*0.1
oil_volume = (Oil_weigt/0.89)/1000
Breather_cap = 12

Ea = 111000
R_mol = 8.3145
O2 = 2
Rs_Values = []
Amb_temp_Night = []
Amb_temp_Day = []
Avg_Ambient = []
Temp_variation = []
Moisture_inAir = []
Moisture_wentInside = []
Moist_absorb_breather = []
Moist_remained_inhaled = []
Days_per_month = []
Ageing_Moist = [87.14240038] #Moisture due to ageing As at now
Total_Moist = [1.7766] #Total Moisture As at now

Days_per_month= [31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31]

# Given year and month
year = 2024
month=1

max_row_val=sheet1.max_row//24

print("max_rows in sheet1",max_row_val)

# Initialize counters
month_year_counter = {
    "month": 1,
```

```
    "year": year
}

# Extract data into a 2D list
data_2d_list = []
for row in sheet.iter_rows(min_row=2,min_col = 2, values_only=True):
    data_2d_list.append(list(row))

Rs_Values=data_2d_list[0]
Amb_temp_Night = data_2d_list[1]
Amb_temp_Day = data_2d_list[2]
Temp_variation = data_2d_list[3]
Moisture_inAir = data_2d_list[4]

def Cal_average () :
    for i in range (0,12,1):
        average = (Amb_temp_Day[i]+Amb_temp_Night[i])/2
        Avg_Ambient.append(average)

def Mositre_Inide () :
    for i in range (0,12,1):
        Moisture_wentInside.append(oil_volume*0.00075*Temp_variation[i]*Moisture_in
Air[i]*Days_per_month[i])

def Breather (moistureabs):

    for i in range (0,12,1):
        Moist_absorb_breather.append(moistureabs)

    return Moist_absorb_breather

def Remaind_Moist() :
    for i in range (0,12,1):

        if Moisture_wentInside[i] > Moist_absorb_breather[i] :
            Moist_remained_inhaled.append(Moisture_wentInside[i]-
Moist_absorb_breather[i])
        elif Moisture_wentInside[i] <= Moist_absorb_breather[i] :
            Moist_remained_inhaled.append(0)

if Breather_cap ==12 :
    Absorbed_Moist = Breather (63)
elif Breather == 6 :
    Absorbed_Moist = Breather (31)

def Cal_Ageing_Moist(dp_Val,dp_Val_Next) :

        if dp_Val >Ageing_Moist= 350 :
```

```
            Ageing_Moist.append((4*(10**8)*(dp_Val**4)-
(0.0001*dp_Val**3)+(0.135*dp_Val**2)-75*dp_Val+17360)*(paper_weight/1000))

        else :
            a=0
            a = ((3*(10**8))*(dp_Val_Next**(-1.72)))-((3*(10**8))*(dp_Val**(-
1.72)))
            Ageing_Moist.append(a)

def Cal_Total_Moist():
        a=0
        length=len(Total_Moist)
        a = ((Total_Moist[length-1]*Oil_weigt)+ (Ageing_Moist[length-1]) +
(Moist_remained_inhaled[month_year_counter["month"]-1]))/Oil_weigt
        Total_Moist.append(a)

Cal_average()
Mositre_Inide()
Remaind_Moist()

hotspot_list=[]
month_year_list=[]

row_counter = {
    "min_row": 2,
    "max_row": 25
}

def get_Excel_Hotspots():

    for rows in sheet1.iter_rows(min_col=6, max_col=6,
min_row=row_counter["min_row"], max_row=row_counter["max_row"]):
        for row in rows:
            cell_value = row.value  # Access the value of the current cell in the
row
            hotspot_list.append(cell_value)
    row_counter["min_row"] += 24
    row_counter["max_row"] += 24

def cal_k_Value(Total_Mois,Hotspot):
    k=0
    if O2 == 0:
        A = math.exp(1.2074 * (Total_Mois-0.5)) * 1.28 * (10 ** 8)
    elif O2 == 1:
        A = math.exp(1.2074 * (Total_Mois-0.5)) * (1.5881 * ((Total_Mois-0.5) ** 2)
- (5.8265 * (Total_Mois-0.5)) + 7.2344) * 1.28 * (10 ** 8)
    elif O2 == 2:
        A = math.exp((1.207 * (Total_Mois-0.5))) * (2.19 * ((Total_Mois-0.5) ** 2)
- (9.874 * (Total_Mois-0.5)) + 13.59) * 1.28 * (10 ** 8)
```

```
    k= A * math.exp(-Ea/ (R_mol*(273 + Hotspot)))

    return k

DP_for_Mosit_Cal = 0
DP_Val = []

def cal_DP(m,dp_dec,y):
    dp=0

    for i in range(0,24,1):
        k=0
        length=len(Total_Moist)
        k=cal_k_Value(Total_Moist[length-1],hotspot_list[i])

        if m ==1 and y== year and i==0 :
            dp = 1/((k*Days_per_month[m-1])+(1/dp_dec))
            DP_Val.append(dp)

        else :
            prev_DP_Index = len(DP_Val)
            dp = 1/((k*Days_per_month[m-1])+(1/DP_Val[prev_DP_Index-1]))
            DP_Val.append(dp)
    return dp

def Life_time() :
    DP_Val = []
    Ageing_Moist = []

    month_year_counter["year"] = year
    month_year_counter["month"] =1
    currentMonth=0
    DP_Val_24 = 0
    DP_Val_24_next=0
    DP_Prev_From_December= 266.583004
    current_year =0
    currentMonth=month_year_counter["month"]

    DP_Val_24 =
cal_DP(currentMonth,DP_Prev_From_December,month_year_counter["year"] )

    while DP_Val_24 > 200 :

        Cal_Total_Moist()

        current_year = month_year_counter["year"]
        currentMonth=month_year_counter["month"]
```

```
        if current_year == year and currentMonth == 1 :
            DP_Val_24_next=cal_DP(currentMonth+1,DP_Prev_From_December,current_year
)
        elif current_year != year and currentMonth == 1  :
            DP_Val_24_next=cal_DP(currentMonth+1,DP_Prev_From_December,current_year
) #3
        else :
            DP_Val_24_next=cal_DP(currentMonth+1,DP_Prev_From_December,current_year
)


        Cal_Ageing_Moist(DP_Val_24,DP_Val_24_next)


        if month_year_counter["month"] == 12 :
            month_year_counter["year"] +=1

            DP_Prev_From_December=DP_Val_24_next
            month_year_counter["month"] = 1

        else:
            month_year_counter["month"] +=1

        currentMonth=month_year_counter["month"]


        DP_Val_24 = DP_Val_24_next

        if currentMonth == 12 :
            Cal_Total_Moist()
            DP_Prev_From_December = DP_Val_24
            DP_Val_24_next=cal_DP(currentMonth,DP_Prev_From_December,current_year)
            Cal_Ageing_Moist(DP_Val_24,DP_Val_24_next)
            DP_Val_24 = DP_Val_24_next
            month_year_counter["year"] +=1
            month_year_counter["month"] =1


    month_year_list.append({"index":i, "year": month_year_counter["year"],"month":
month_year_counter["month"]})

sheet1.cell(row=1, column=10, value='LifeTime-Years')
sheet1.cell(row=1, column=11, value='LifeTime-MOnths')

for i in range(1,max_row_val+1,1):
    hotspot_list=[]
    Ageing_Moist = [87.14240038]
    DP_Val = []
```

```
    Total_Moist = [1.7766]
    get_Excel_Hotspots()
    Life_time()

excel_counter = 1

for entry in month_year_list:
    if excel_counter < len(month_year_list)+1:
        sheet1.cell(row=(excel_counter * 24) + 1, column=10, value=entry["year"])
        sheet1.cell(row=(excel_counter*24)+1, column=11, value=entry["month"])
        excel_counter += 1

for item in month_year_list:
    if item["year"] > 2020:
        print(item)

TF_workbook.save('example.xlsx')
```

Appendix S - Transformer Life Estimation Model – Results – Madampe TF 2

Temp_FG1	Temp_FG2	Increased Load %	Initial Load	Increased Load	Hotspot Temp	Runtime Hours_ONAN	Runtime Hours_FG1	Runtime Hours_FG2	LifeTime-Years
32	44	0	260	260	52.3588	0	0	1	
32	44	0	253	253	48.23712	0	0	2	
32	44	0	252	252	47.86191	0	0	3	
32	44	0	257	257	47.98439	0	0	4	
32	44	0	288	288	49.33748	0	0	5	
32	44	0	315	315	51.95525	0	0	6	
32	44	0	308	308	53.15492	0	0	7	
32	44	0	309	309	52.80282	0	0	8	
32	44	0	331	331	53.74217	0	0	9	
32	44	0	338	338	55.28462	0	0	10	
32	44	0	353	353	56.33164	0	0	11	
32	44	0	351	351	57.1442	0	0	12	
32	44	0	335	335	56.34744	0	0	13	

32	44	0	338	338	55.51847	0	0	14	
32	44	0	341	341	55.82081	0	0	15	
32	44	0	339	339	55.91456	0	0	16	
32	44	0	334	334	55.58779	0	0	17	
32	44	0	338	338	55.45983	0	0	18	
32	44	0	375	375	57.30078	0	0	19	
32	44	0	372	372	59.42825	0	0	20	
32	44	0	353	353	58.40468	0	0	21	
32	44	0	321	321	55.89627	0	0	22	
32	44	0	295	295	52.99445	0	0	23	
32	44	0	269	269	50.59804	0	0	24	2046
32	44	5	260	273	52.81732	0	0	1	
32	44	5	253	265.65	49.32624	0	0	2	
32	44	5	252	264.6	48.91819	0	0	3	
32	44	5	257	269.85	49.05129	0	0	4	
32	44	5	288	302.4	50.52231	0	0	5	

32	44	5	315	330.75	53.3677	0	0	6	
32	44	5	308	323.4	54.66958	0	0	7	
32	44	5	309	324.45	54.28756	0	0	8	
32	44	5	331	347.55	55.30875	0	0	9	
32	44	5	338	354.9	56.98281	0	0	10	
32	44	5	353	370.65	58.12005	0	0	11	
32	44	5	351	368.55	59.00058	0	0	12	
32	44	5	335	351.75	58.13467	0	0	13	
32	44	5	338	354.9	57.2364	0	0	14	
32	44	5	341	358.05	57.56461	0	0	15	
32	44	5	339	355.95	57.66598	0	0	16	
32	44	5	334	350.7	57.31105	0	0	17	
32	44	5	338	354.9	57.17282	0	0	18	
32	44	5	375	393.75	59.17389	0	0	19	
32	44	5	372	390.6	61.47883	0	0	20	
32	44	5	353	370.65	60.36661	0	0	21	

32	44	5	321	337.05	57.64371	0	0	22	
32	44	5	295	309.75	54.49436	0	0	23	
32	44	5	269	282.45	51.8918	0	0	24	2042
32	44	10	260	286	53.29162	0	0	1	
32	44	10	253	278.3	50.45287	0	0	2	
32	44	10	252	277.2	50.01104	0	0	3	
32	44	10	257	282.7	50.15516	0	0	4	
32	44	10	288	316.8	51.74809	0	0	5	
32	44	10	315	346.5	54.82802	0	0	6	
32	44	10	308	338.8	56.23458	0	0	7	
32	44	10	309	339.9	55.82189	0	0	8	
32	44	10	331	364.1	56.92777	0	0	9	
32	44	10	338	371.8	58.73708	0	0	10	
32	44	10	353	388.3	59.96738	0	0	11	
32	44	10	351	386.1	60.91752	0	0	12	
32	44	10	335	368.5	59.98012	0	0	13	

32	44	10	338	371.8	59.01091	0	0	14	
32	44	10	341	375.1	59.36575	0	0	15	
32	44	10	339	372.9	59.47488	0	0	16	
32	44	10	334	367.4	59.0909	0	0	17	
32	44	10	338	371.8	58.94225	0	0	18	
32	44	10	375	412.5	61.10891	0	0	19	
32	44	10	372	409.2	63.59566	0	0	20	
32	44	10	353	388.3	62.39182	0	0	21	
32	44	10	321	353.1	59.44786	0	0	22	
32	44	10	295	324.5	56.04383	0	0	23	
32	44	10	269	295.9	53.22899	0	0	24	2039
32	44	15	260	299	53.78149	0	0	1	
32	44	15	253	290.95	51.61617	0	0	2	
32	44	15	252	289.8	51.13967	0	0	3	
32	44	15	257	295.55	51.2952	0	0	4	
32	44	15	288	331.2	53.01398	0	0	5	

32	44	15	315	362.25	56.33519	0	0	6	
32	44	15	308	354.2	57.84879	0	0	7	
32	44	15	309	355.35	57.40472	0	0	8	
32	44	15	331	380.65	58.59809	0	0	9	
32	44	15	338	388.7	60.54618	0	0	10	
32	44	15	353	405.95	61.87235	0	0	11	
32	44	15	351	403.65	62.89367	0	0	12	
32	44	15	335	385.25	61.88247	0	0	13	
32	44	15	338	388.7	60.84074	0	0	14	
32	44	15	341	392.15	61.22296	0	0	15	
32	44	15	339	389.85	61.33995	0	0	16	
32	44	15	334	384.1	60.92604	0	0	17	
32	44	15	338	388.7	60.76689	0	0	18	
32	44	15	375	431.25	63.10454	0	0	19	
32	44	15	372	427.8	65.77726	0	0	20	
32	44	15	353	405.95	64.47886	0	0	21	

32	44	15	321	369.15	61.30742	0	0	22	
32	44	15	295	339.25	57.6417	0	0	23	
32	44	15	269	309.35	54.6086	0	0	24	2036
32	44	20	260	312	54.28678	0	0	1	
32	44	20	253	303.6	52.81537	0	0	2	
32	44	20	252	302.4	52.30332	0	0	3	
32	44	20	257	308.4	52.47066	0	0	4	
32	44	20	288	345.6	54.31916	0	0	5	
32	44	20	315	378	57.88825	0	0	6	
32	44	20	308	369.6	59.51115	0	0	7	
32	44	20	309	370.8	59.03502	0	0	8	
32	44	20	331	397.2	60.31865	0	0	9	
32	44	20	338	405.6	62.40896	0	0	10	
32	44	20	353	423.6	63.83373	0	0	11	
32	44	20	351	421.2	64.92777	0	0	12	
32	44	20	335	402	63.8405	0	0	13	

32	44	20	338	405.6	62.72472	0	0	14	
32	44	20	341	409.2	63.13505	0	0	15	
32	44	20	339	406.8	63.26001	0	0	16	
32	44	20	334	400.8	62.8153	0	0	17	
32	44	20	338	405.6	62.64556	0	0	18	
32	44	20	375	450	65.15952	0	0	19	
32	44	20	372	446.4	68.02225	0	0	20	
32	44	20	353	423.6	66.62641	0	0	21	
32	44	20	321	385.2	63.22115	0	0	22	
32	44	20	295	354	59.28693	0	0	23	
32	44	20	269	322.8	56.02971	0	0	24	2033

This will continue until the iterations are over by the set conditions.

Appendix T – Cost Optimization Model Code

```
import openpyxl
import numpy as np
import numpy_financial as npf

# Load an hotspot values Excel file
TF_workbook = openpyxl.load_workbook('example.xlsx')
sheet1 = TF_workbook.active
max_row_val=sheet1.max_row//24

Unit_cost = 48
fg1_kW = 3*3
fg2_kW = 3*6

# Given year and month
year = 2024
month= 1

TF_MVA = 31.5*(10**6)
TF_LV_V = 33000
TF_Load_Loss_ONAF = 117641
Avg_TF_Cost = 1724221 # in USD
Avg_MVA_Cost_Year =  915/12 #1281/12  #in USD
exch_rate = 300

Fan_Cost = 9400  #USD for 1 fan
Fan_lifetime = 30 #years
Fan_runtime = 7560  #per Year  #21*30*12
#Average_fan_hours = 87    #3*13+6*8 per 24 hours
Cost_per_Fan_per_hour = Fan_Cost / (Fan_runtime * Fan_lifetime )


load_initial = [260, 253, 252, 257, 288, 315, 308, 309, 331, 338, 353, 351, 335,
338, 341, 339, 334, 338, 375, 372, 353, 321, 295, 269 ]

LV_I = TF_MVA/(1.732*TF_LV_V)
TF_R = TF_Load_Loss_ONAF/(LV_I**2)

print(TF_R)
#print(Avg_MVA_Cost_Year)

sheet1.cell(row=1, column=12, value='Load Loss')
sheet1.cell(row=1, column=13, value='Aux. Losses')
sheet1.cell(row=1, column=14, value='Saving due to Increase Load')
sheet1.cell(row=1, column=15, value='Addi_aux_cost')
sheet1.cell(row=1, column=16, value='Addi_load_loss_cost')
sheet1.cell(row=1, column=17, value='Loading_Saving')
sheet1.cell(row=1, column=18, value='Replacement_Saving')
```

```
sheet1.cell(row=1, column=19, value='NPV')

# CALCULATION OF THE COST OF LOAD LOSSES FOR A YEAR

row_counter = {
    "min_row": 2,
    "max_row": 25
}


def cal_load_loss_cost():
    load_loss_cost=0
    load_loss_val = 0
    for rows in sheet1.iter_rows(min_col=5, max_col=5,
min_row=row_counter["min_row"], max_row=row_counter["max_row"]):
       for row in rows:
            load_loss_val += (row.value**2)*TF_R*30/1000
            cost = (row.value**2)*TF_R*30*Unit_cost/1000
            load_loss_cost += cost

    sheet1.cell(row =row_counter["max_row"], column=12, value= load_loss_val )
    row_counter["min_row"] += 24
    row_counter["max_row"] += 24
    return load_loss_cost

# CALCULATION OF THE COST OF AUXILIARY LOSSES FOR A YEAR
# Define the column indices you're interested in (0-based)
fg1_runtime_column_index = 8
fg2_runtime_column_index = 9
fg1_runtime_total_value = 0
fg2_runtime_total_value = 0
Aux_loss_cost=0
excel_row_counter = {
    "row_number": 25
}

def cal_Aux_loss_cost():
    Aux_loss_Val=0
    # Retrieve the values from the specified cells in the desired row
    fg1_runtime_total_value = sheet1.cell(row=excel_row_counter["row_number"],
column=fg1_runtime_column_index).value
    fg2_runtime_total_value = sheet1.cell(row=excel_row_counter["row_number"],
column=fg2_runtime_column_index).value
    Aux_loss_Val = ((fg1_kW*fg1_runtime_total_value) +
(fg2_kW*fg2_runtime_total_value))*30

    maintenance_cost = (fg2_runtime_total_value + (fg1_runtime_total_value +
fg2_runtime_total_value ))*30*Cost_per_Fan_per_hour*300*3
```

```
    Aux_loss_cost = (((fg1_kW *fg1_runtime_total_value) +
(fg2_kW*fg2_runtime_total_value))*30*Unit_cost) + maintenance_cost

    if fg2_runtime_total_value == 24:
        Aux_loss_cost = Aux_loss_cost + 15000*300*6


    sheet1.cell(row =excel_row_counter["row_number"], column=13, value=
Aux_loss_Val )
    excel_row_counter["row_number"] += 24
    return Aux_loss_cost

percentage_increase = 0
# CALCULATION OF SAVING DUE TO INCREASED LOAD FOR A YEAR
row_counter_sav = {
    "min_row": 2,
    "max_row": 25
}
def cal_incr_load_saving():
    Incr_load_saving=0
    Saving_val = 0
    for rows in sheet1.iter_rows(min_col=5, max_col=5,
min_row=row_counter_sav["min_row"], max_row=row_counter_sav["max_row"]):
       for row in rows:
            percentage_increase =  sheet1.cell(row=row_counter_sav["min_row"],
column= 3).value

            Saving_val += (1.732*row.value)*TF_LV_V*30/1000
            savi = (1.732*row.value*TF_LV_V)*30*Avg_MVA_Cost_Year*exch_rate/10**6

            Incr_load_saving += savi
            sheet1.cell(row =row_counter_sav["max_row"], column=14, value=
Saving_val )
    row_counter_sav["min_row"] += 24
    row_counter_sav["max_row"] += 24
    return Incr_load_saving

# Define the column indices you're interested in (0-based)
Life_Year_column_index = 10
Life_MOnth_column_index = 11


Life_in_Years = 0
Life_in_Months = 0
year_row_counter = {
    "row_number": 25
}

def cal_Total_Periods_months():
```

```
    Life_in_Years = 0
    Life_in_Months = 0

    # Retrieve the values from the specified cells in the desired row
    Life_in_Years = sheet1.cell(row=year_row_counter["row_number"],
column=Life_Year_column_index).value
    Life_in_Months = sheet1.cell(row=year_row_counter["row_number"],
column=Life_MOnth_column_index).value
    Total_Periods_in_months = ((Life_in_Years - year))*12 + Life_in_Months


    year_row_counter["row_number"] += 24

    return Total_Periods_in_months

new_counter=1
disc_rate = 0.00833
npv_value = []

#Calculation for Default Condition
prev_life_year = 2037
prev_life_month = 3

prev_FG1_hours = 13
prev_fg2_hours = 8

present_m = ((prev_life_year-2024))*12 +prev_life_month
prev_aux_Loss_cost =
(((fg1_kW*prev_FG1_hours)+(fg2_kW*prev_fg2_hours))*30*Unit_cost) +
(fg2_runtime_total_value + (fg1_runtime_total_value + fg2_runtime_total_value
))*30*Cost_per_Fan_per_hour*300*3
prev_load_loss_cost = 0
prev_loading_cost = 0

for i in range (0,24,1) :
    prev_load_loss_cost = sum((value**2)*TF_R*30*Unit_cost/1000 for value in
load_initial)
    prev_loading_cost =
sum(value*1.732*TF_LV_V*30*Avg_MVA_Cost_Year*exch_rate/10**6 for value in
load_initial)


prev_aux_Loss_cost_Flow = [prev_aux_Loss_cost]*present_m
prev_load_loss_cost_Flow = [prev_load_loss_cost]*present_m
prev_loading_cost_Flow = [prev_loading_cost]*present_m

npv_prev_aux_cost = npf.npv(disc_rate, prev_aux_Loss_cost_Flow)
npv_prev_load_loss_cost = npf.npv(disc_rate, prev_load_loss_cost_Flow)
npv_prev_loading_cost = npf.npv(disc_rate, prev_loading_cost_Flow)
```

```
npv_prev_replacement_cost = (Avg_TF_Cost*exch_rate) / ((1 + disc_rate) **
(present_m+1))

#________________________________________________________________#
aux = 0
load_loss = 0
count = 0

for i in range(1,max_row_val+1,1):

    m = cal_Total_Periods_months()

    new_aux_Loss_cost_Flow = [cal_Aux_loss_cost()]*m
    new_load_loss_cost_Flow = [cal_load_loss_cost()]*m
    new_loading_cost_Flow = [cal_incr_load_saving()]*m

    npv_new_aux_cost = npf.npv(disc_rate, new_aux_Loss_cost_Flow)
    npv_new_load_loss_cost = npf.npv(disc_rate, new_load_loss_cost_Flow)
    npv_new_loading_cost = npf.npv(disc_rate, new_loading_cost_Flow)

    npv_new_replacement_cost = (Avg_TF_Cost*exch_rate) / ((1 + disc_rate) ** (m+1))


    Addi_aux_cost = npv_new_aux_cost - npv_prev_aux_cost
    Addi_load_loss_cost = npv_new_load_loss_cost - npv_prev_load_loss_cost
    Loading_Saving = npv_new_loading_cost - npv_prev_loading_cost
    Replacement_Saving = npv_prev_replacement_cost - npv_new_replacement_cost

    npv_value.append((Replacement_Saving +  Loading_Saving ) - (Addi_aux_cost +
Addi_load_loss_cost))

    sheet1.cell(row=(new_counter * 24) + 1, column=15, value=Addi_aux_cost)
    sheet1.cell(row=(new_counter * 24) + 1, column=16, value=Addi_load_loss_cost)
    sheet1.cell(row=(new_counter * 24) + 1, column=17, value=Loading_Saving)
    sheet1.cell(row=(new_counter * 24) + 1, column=18, value=Replacement_Saving)

    a = Mnpv_valueonthly_Net_Value = 0


    print(count)

    count += 1
    new_counter +=1

excel_npv_counter = 1

for entry in npv_value:
```

```
    if excel_npv_counter < len(npv_value)+1:
        sheet1.cell(row=(excel_npv_counter * 24) + 1, column=19, value=entry/10**6)
        excel_npv_counter += 1


Max_NPV=max(npv_value)
print("Max NPV is :", Max_NPV/10**6)


sheet2= TF_workbook.worksheets[1]

sheet2.cell(row=1, column=1, value='Temp_FG1')
sheet2.cell(row=1, column=2, value='Temp_FG2')
sheet2.cell(row=1, column=3, value='Increased Load%')
sheet2.cell(row=1, column=4, value='Runtime Hours_ONAN')
sheet2.cell(row=1, column=5, value='Runtime Hours_FG1')
sheet2.cell(row=1, column=6, value='Runtime Hours_FG2')
sheet2.cell(row=1, column=7, value='LifeTime-Years')
sheet2.cell(row=1, column=8, value='LifeTime-Months')
sheet2.cell(row=1, column=9, value='Load Losses')
sheet2.cell(row=1, column=10, value='Aux. Losses')
sheet2.cell(row=1, column=11, value='Saving due to Increase Load')
sheet2.cell(row=1, column=12, value='Addi_aux_cost')
sheet2.cell(row=1, column=13, value='Addi_load_loss_cost')
sheet2.cell(row=1, column=14, value='Loading_Saving')
sheet2.cell(row=1, column=15, value='Replacement_Saving')
sheet2.cell(row=1, column=16, value='NPV (MLKR)')

sheet1_row_val=25
sheet2_row_count=0
for i in range(1,sheet1.max_row+1,24):

    sheet2.cell(row=sheet2_row_count+2, column=1,
value=sheet1.cell(row=sheet1_row_val, column=1).value)
    sheet2.cell(row=sheet2_row_count+2, column=2,
value=sheet1.cell(row=sheet1_row_val, column=2).value)
    sheet2.cell(row=sheet2_row_count+2, column=3,
value=sheet1.cell(row=sheet1_row_val, column=3).value)
    sheet2.cell(row=sheet2_row_count+2, column=4,
value=sheet1.cell(row=sheet1_row_val, column=7).value)
    sheet2.cell(row=sheet2_row_count+2, column=5,
value=sheet1.cell(row=sheet1_row_val, column=8).value)
    sheet2.cell(row=sheet2_row_count+2, column=6,
value=sheet1.cell(row=sheet1_row_val, column=9).value)
    sheet2.cell(row=sheet2_row_count+2, column=7,
value=sheet1.cell(row=sheet1_row_val, column=10).value)
    sheet2.cell(row=sheet2_row_count+2, column=8,
value=sheet1.cell(row=sheet1_row_val, column=11).value)
```

```
    sheet2.cell(row=sheet2_row_count+2, column=9,
value=sheet1.cell(row=sheet1_row_val, column=12).value)
    sheet2.cell(row=sheet2_row_count+2, column=10,
value=sheet1.cell(row=sheet1_row_val, column=13).value)
    sheet2.cell(row=sheet2_row_count+2, column=11,
value=sheet1.cell(row=sheet1_row_val, column=14).value)
    sheet2.cell(row=sheet2_row_count+2, column=12,
value=sheet1.cell(row=sheet1_row_val, column=15).value)
    sheet2.cell(row=sheet2_row_count+2, column=13,
value=sheet1.cell(row=sheet1_row_val, column=16).value)
    sheet2.cell(row=sheet2_row_count+2, column=14,
value=sheet1.cell(row=sheet1_row_val, column=17).value)
    sheet2.cell(row=sheet2_row_count+2, column=15,
value=sheet1.cell(row=sheet1_row_val, column=18).value)
    sheet2.cell(row=sheet2_row_count+2, column=16,
value=sheet1.cell(row=sheet1_row_val, column=19).value)
    sheet1_row_val +=24
    sheet2_row_count +=1

print("NPV Aux Previous",npv_prev_aux_cost)
print("NPV Loading Previous ",npv_prev_loading_cost)
print("NPV Load Loss Previous ",npv_prev_load_loss_cost)
print("NPV Replacement cost Previous ",npv_prev_replacement_cost)
print("------------------")
print("New load loss flow :", new_load_loss_cost_Flow)
print("NPV value list :", npv_value)


rows_to_delete = []

# Iterate through the rows and columns to search for cells with a value of 0
for row in sheet2.iter_rows(min_col=3, max_col=3):
    for cell in row:
        if cell.value == 0:
            rows_to_delete.append(row[0].row)  # Store the row index

# Reverse the list to avoid issues with shifting rows during deletion
rows_to_delete.reverse()

# Delete the rows from the sheet
for row_index in rows_to_delete:
    sheet2.delete_rows(row_index)


TF_workbook.save('example.xlsx')
```

Appendix U - Cost Optimization Model Results

Temp_ FG1	Temp_ FG2	Increased Load %	Runtime Hours_ ONAN	Runtime Hours_F G1	Runtime Hours_ FG2	LifeTime-Years	NPV (MLKR)
36	52	5	0	2	22	2042	5197.46
40	52	5	0	2	22	2042	5197.46
44	52	5	0	2	22	2042	5197.46
48	52	5	0	2	22	2042	5197.46
36	56	5	0	6	18	2040	4184.48
40	56	5	0	6	18	2040	4184.48
44	56	5	0	6	18	2040	4184.48
48	56	5	0	6	18	2040	4184.48
52	56	5	1	4	19	2040	4123.30
52	52	5	2	0	22	2040	3996.68
36	52	10	0	2	22	2038	3855.86
40	52	10	0	2	22	2038	3855.86
44	52	10	0	2	22	2038	3855.86
48	52	10	0	2	22	2038	3855.86
36	56	10	0	4	20	2037	3292.93
40	56	10	0	4	20	2037	3292.93
44	56	10	0	4	20	2037	3292.93
48	56	10	0	4	20	2037	3292.93
36	36	5	0	0	24	2042	2701.48
36	40	5	0	0	24	2042	2701.48

36	44	5	0	0	24	2042	2701.48
36	48	5	0	0	24	2042	2701.48
40	40	5	0	0	24	2042	2701.48
40	44	5	0	0	24	2042	2701.48
40	48	5	0	0	24	2042	2701.48
44	44	5	0	0	24	2042	2701.48
44	48	5	0	0	24	2042	2701.48
48	48	5	0	0	24	2042	2701.48
52	52	10	2	0	22	2037	2605.09
36	52	15	0	1	23	2036	2535.72
40	52	15	0	1	23	2036	2535.72
44	52	15	0	1	23	2036	2535.72
48	52	15	0	1	23	2036	2535.72
52	56	10	2	1	21	2036	2152.65
52	52	15	1	0	23	2035	2112.86
36	56	15	0	3	21	2035	1896.66
40	56	15	0	3	21	2035	1896.66
44	56	15	0	3	21	2035	1896.66
48	56	15	0	3	21	2035	1896.66
36	36	10	0	0	24	2039	1846.68
36	40	10	0	0	24	2039	1846.68
36	44	10	0	0	24	2039	1846.68
36	48	10	0	0	24	2039	1846.68
40	40	10	0	0	24	2039	1846.68

40	44	10	0	0	24	2039	1846.68
40	48	10	0	0	24	2039	1846.68
44	44	10	0	0	24	2039	1846.68
44	48	10	0	0	24	2039	1846.68
48	48	10	0	0	24	2039	1846.68
52	56	15	1	1	22	2035	1786.62
56	56	5	5	0	19	2037	1467.96
36	60	5	0	14	10	2037	1133.26
40	60	5	0	14	10	2037	1133.26
44	60	5	0	14	10	2037	1133.26
48	60	5	0	14	10	2037	1133.26
52	60	5	0	14	10	2037	1133.26
56	56	10	3	0	21	2035	882.27
56	56	15	2	0	22	2034	635.58
36	60	15	0	8	16	2034	397.87
40	60	15	0	8	16	2034	397.87
44	60	15	0	8	16	2034	397.87
48	60	15	0	8	16	2034	397.87
52	60	15	0	8	16	2034	397.87
36	36	15	0	0	24	2036	343.53
36	40	15	0	0	24	2036	343.53
36	44	15	0	0	24	2036	343.53
36	48	15	0	0	24	2036	343.53
40	40	15	0	0	24	2036	343.53

40	44	15	0	0	24	2036	343.53
40	48	15	0	0	24	2036	343.53
44	44	15	0	0	24	2036	343.53
44	48	15	0	0	24	2036	343.53
48	48	15	0	0	24	2036	343.53
36	56	20	0	2	22	2033	86.27
40	56	20	0	2	22	2033	86.27
44	56	20	0	2	22	2033	86.27
48	56	20	0	2	22	2033	86.27
52	56	20	0	2	22	2033	86.27
56	60	5	3	9	12	2036	44.95
36	60	10	0	13	11	2035	36.75
40	60	10	0	13	11	2035	36.75
44	60	10	0	13	11	2035	36.75
48	60	10	0	13	11	2035	36.75
52	60	10	0	13	11	2035	36.75
56	60	15	1	7	16	2034	-224.35
56	60	10	1	12	11	2034	-410.72
36	36	20	0	0	24	2033	-1542.95
36	40	20	0	0	24	2033	-1542.95
36	44	20	0	0	24	2033	-1542.95
36	48	20	0	0	24	2033	-1542.95
36	52	20	0	0	24	2033	-1542.95
40	40	20	0	0	24	2033	-1542.95

40	44	20	0	0	24	2033	-1542.95
40	48	20	0	0	24	2033	-1542.95
40	52	20	0	0	24	2033	-1542.95
44	44	20	0	0	24	2033	-1542.95
44	48	20	0	0	24	2033	-1542.95
44	52	20	0	0	24	2033	-1542.95
48	48	20	0	0	24	2033	-1542.95
48	52	20	0	0	24	2033	-1542.95

The top 100 results are tabulated.