

**Department of Electrical and Computer Engineering**

**FURAN MEASUREMENT IN TRANSFORMER OIL  
BY UV-VIS SPECTROSCOPY USING FUZZY LOGIC  
APPROACH**

**LAI SIN PIN**

**This thesis is presented as part of the requirement for the award of the  
Degree of Master of Electrical Engineering  
of the Curtin University of Technology**

**January 2009**

## **DECLARATION**

This thesis contains no material that has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledge has been made.

Signature: \_\_\_\_\_

## **SYNOPSIS**

An Ultraviolet to Visible (UV-Vis) spectroscopic analysis based on fuzzy logic approach has been developed for furan content measurement in transformer oil. Following the successful identification and quantification of furan derivatives in transformer oil by ASTM D5837 standard, the new approach is able to approximate the furan content more conveniently and economically. As furan concentration level would determine the absorption intensity in UV-Vis spectral range, the fuzzy logic software model developed would exploit this characteristic to aggregate the furans content level in transformer oil. The UV-Vis spectral response at other ambient temperature is also studied. The proposed technique provides a convenient alternative to conventional method of furan measurement by High Performance Liquid Chromatography (HPLC) or Gas Chromatography Mass Spectrometry (GC/MS) in ASTM D5837 Standard.

## **ACKNOWLEDGEMENT**

The author would like to express his sincere thanks to his supervisor, Prof. Syed Islam, for guidance and encouragement throughout the duration of the project. Without his teaching with regard to the theoretical and simulation aspects, the author would not have completed his project.

The author would also like to express his gratitude to his co-supervisor and also to a good friend, Dr. Ahmed Abu-Siada, for his support and guidance throughout the years of research.

The author would like to show his appreciation to Mr. Gary Lenco from Testing and Commissioning Services (Australia) Pty.Ltd. and to Mr Ming Zaw from SGS (Australia), for their generosity in providing technical advice and the facilities for the completion of the project.

This work was partially supported by the Cooperative Research Centre for Integrated Engineering Asset Management (CIEAM). The author would therefore like to extend his appreciation for their support.

Finally, the author would like to thank his beloved parents, Lai Jin Nyap and Phang Sze Ching, for their encouragement, as well as their financial support throughout his studies.

## LIST OF PUBLICATIONS

It is acknowledged that part of the thesis has already been published in some of the conferences.

- S. P. Lai, A. Abu-Siada, S. M. Islam, and G. Lenco, "Correlation between UV-Vis spectral response and furan measurement of transformer oil," in *Condition Monitoring and Diagnosis, 2008. CMD 2008. International Conference on*, 2008, pp. 659-662.
- S. P. Lai, A. Abu-Siada, and S. M. Islam, "Review of Spectral Response for Aged Transformer Insulation Assessment Techniques," in *The Eighth Postgraduate Electrical Engineering & Computing Symposium*, Perth, 2007, pp. 60-66.
- S. Lai, A. Abu-Siada, S. Islam" A Novel Fuzzy Logic Approach for Furan Concentration Estimation in Transformer Oil", submitted (August 2008) to IEEE Transactions on Power Delivery.
- S. Lai, A. Abu-Siada, S. Islam," Furan Measurement in Transformer Oil by UV- Vis Spectral Response Using Fuzzy Logic", Paper accepted for oral presentation at ICECE'08 that will be held in Bangladesh November 2008.
- Sin P. Lai, Syed M. Islam, and A. Abu-Siada, "A Novel Technique for Furan Estimation in Transformer Oil", Submitted (December 2008) for the contest of IEEE Power Engineering Society's Student Prize Paper Award in Honor of T. Burke Hayes.
- Abu-Siada, S. Islam and S. Lai," Remnant Life Estimation of Power Transformer using Oil UVvis Spectral Response", Paper accepted for presentation at IEEE PSCE09 that will be held in USA March 2009.
- Abu-Siada, S. Islam and S. Lai," A Novel Application of Gene Expression Programming in Transformer Diagnostics", Paper accepted for oral presentation at AUPEC'08 that will be held in Sydney, December 2008
- Abu-Siada, S. Islam and S. Lai," Correlation of Furan concentration and Spectral Response of Transformer Oil", submitted (August 2008) to IEEE Transactions on Dielectric and Electrical Insulations.

---

**INDEX**

SYNOPSIS .....	I
ACKNOWLEDGEMENT .....	II
LIST OF PUBLICATIONS .....	III
INDEX .....	IV
LIST OF FIGURES .....	VII
LIST OF TABLES .....	IX
ABBREVIATIONS .....	X
SYMBOLS .....	XI
1 INTRODUCTION .....	1
1.1 Power Transformer.....	1
1.2 Power Transformer Failures.....	2
1.3 Difficulties with Power Transformer Insulation Strength Assessment.....	3
1.4 Research Objectives .....	5
1.5 Organization of the Thesis .....	5
2 POWER TRANSFORMER INSULATION.....	7
2.1 Introduction .....	7
2.2 Deterioration Mechanisms in Transformer Insulation .....	8
2.3 Diagnostic Techniques in Power Transformer Insulation.....	9
2.3.1 Electrical Diagnostic Techniques.....	10
2.3.2 Chemical Diagnostic Techniques.....	11
2.4 New Diagnostic Methods by Spectroscopy Analysis .....	13
2.5 Furanic Compounds in Transformer Oil.....	15
2.6 Summary .....	20
3 EXPERIMENT AND RESULTS .....	21

---

3.1	Introduction .....	21
3.2	Experimental Work .....	22
3.2.1	IEC 61125 Unused Hydrocarbon-based Insulating Liquids-test Methods for Evaluating the Oxidation Stability .....	22
3.2.2	ASTM D5837 (Modified) Standard Test Method for Furanic Compounds in Electrical Insulating Liquids by Gas Chromatography-Mass Spectrometry (GC/MS) .....	27
3.2.3	ASTM E275 Standard Practice for Describing and Measuring Performance of Ultraviolet, Visible, and Near-Infrared Spectrometers .....	31
3.2.4	Dilution of High Furanic Oil Samples .....	38
3.2.5	ASTM D 923 Standard Practice for Sampling Electrical Insulating Liquids	39
3.3	Result and Discussion .....	41
3.3.1	Furan Measurement by ASTM D 5837.....	41
3.3.2	Furan Measurement by UV-Vis Spectroscopy at 20°C .....	44
3.3.3	Furan Measurement by UV-Vis Spectral Response at 25°C .....	48
3.4	Summary .....	52
4	FUZZY LOGIC MODELING .....	53
4.1	Introduction .....	53
4.2	Fuzzy Logic for Furan Estimation .....	53
4.3	Model Design Approach .....	55
4.3.1	Fuzzification of Input Variables .....	55
4.3.2	Apply Fuzzy Operator.....	58
4.3.3	Apply Implication Method.....	59
4.3.4	Aggregate All Outputs .....	59

---

4.3.5	Defuzzification.....	60
4.4	System Modeling in MATLAB .....	61
4.5	Verification of Simulation Model .....	65
4.6	Comparison between ASTM D5837 and UV-Vis Spectroscopy with Fuzzy Logic	66
4.7	Summary .....	67
5	CONCLUSION AND FUTURE RESEARCH.....	68
5.1	Conclusion .....	68
5.2	Further Recommendations .....	68
5.3	Key Contribution.....	69
	REFERENCE.....	71
	APPENDIX A: FUZZY LOGIC.....	76
	APPENDIX B: PARAMETERS FOR FUZZY EQUATION .....	80
	APPENDIX C: IF-THEN RULES .....	82
	APPENDIX D: DP ESTIMATION .....	84

## LIST OF FIGURES

Figure 1-1 Power transformer, front view .....	1
Figure 1-2: Picture of transformer explosion .....	2
Figure 2-1: Three-phase oil-cooled transformer with cover cut away.....	7
Figure 2-2 Schematic diagram of insulation system and deterioration mechanism inside a transformer.....	9
Figure 2-3: Degradation correlation in 320-335nm .....	15
Figure 2-4 Furanic compounds detectable in transformer oil that has been in contact with degraded cellulosic insulation.....	16
Figure 2-5 Production of 5-HMF and 2-FAL from LG.....	17
Figure 2-6 Production of 5-HMF and 2-FAL from hydrolytic thermal degradation of cellulose; R represents the cellulose chain.....	17
Figure 2-7: Furanic compounds detected in oil containing paper as a function of temperature.....	18
Figure 2-8: Furanic compounds detected in Kraft paper as a function of temperature .....	18
Figure 2-9: Development of 2-FAL with time at temperature of 85°C. (solid line - air & oil A, dotted line - air & oil B, dashed line - oil A only).....	19
Figure 2-10: Correlation of 2-FAL with DP in dried pressboard at different aging temperatures (DP <sub>0</sub> is the initial DP value of pressboard prior to aging) .....	19
Figure 3-1: Sample of heating block with 8 holes .....	23
Figure 3-2: Sample of test tube used as according to the standard .....	24
Figure 3-3: Oxidation tube and absorption tube assembly.....	24
Figure 3-4 Test sample consist of copper strip wrapped with transformer paper impregnated in a 25g of new transformer oil. ....	26
Figure 3-5 Laboratory aging transformer oil assembly in compliance with IEC 61125.....	26
Figure 3-6: Gas Chromatography-Mass Spectrometer schematic .....	27
Figure 3-7 Example of chromatograms for furan derivatives identification by HPLC .....	28
Figure 3-8 GC/MS equipment used in this project .....	30
Figure 3-9: Light Spectrum in nanometers .....	31
Figure 3-10: Schematic diagram of Beer-Lambert Law .....	32
Figure 3-11 Schematic diagram of UV-Vis spectroscopic measurement system. ....	34
Figure 3-12 UV-Vis Spectroscopy furan measurement system.....	37
Figure 3-13 Sample collection of transformer oil with different furan content.....	40
Figure 3-14: Sample collections of oil stored according to ASTM D923 .....	40
Figure 3-15 UV-Vis absorption spectral response at various furans content level...	45
Figure 3-16 Spectral response bandwidth with respect to furan content .....	46
Figure 3-17 Maximum absorption peak ( $A_{\lambda}$ ) with respect to furan content.....	47
Figure 3-18 Linearity between bandwidth and absorption peak in relation to 2-FAL concentration level .....	48
Figure 3-19: UV-Vis spectral response at ambient temperature of 25°C .....	49
Figure 3-20 Spectral bandwidth variation range for ambient temperature between 20°C and 25°C at different furans concentration .....	50
Figure 3-21 Maximum absorption peak variation range between ambient temperature of 20°C and 25°C at different furans concentration.....	51
Figure 4-1 Input-output map for furan content estimation.....	54
Figure 4-2 Fuzzy Inference flow chart for model development .....	55

---

Figure 4-3: Gaussian combination membership function curve .....	56
Figure 4-4: Triangular membership function curve .....	57
Figure 4-5: Graphical illustration of fuzzification for input bandwidth parameter ..	58
Figure 4-6: Graphical presentation for application of the Operator AND .....	58
Figure 4-7: Schematic diagram of applying implication method .....	59
Figure 4-8: Schematic diagram of aggregation of all outputs.....	60
Figure 4-9: Schematic diagram of defuzzification.....	61
Figure 4-10 Gaussian combination membership function curves for UV-Vis absorption bandwidth .....	61
Figure 4-11 Gaussian membership function for maximum absorption peak.....	62
Figure 4-12 Triangular membership function for furan concentration output.....	62
Figure 4-13 Furans estimation fuzzy logic model .....	63
Figure 4-14 Furans concentration level estimation display based on the bandwidth and absorption peak inputs.....	64
Figure 4-15 Three-dimensional mapping from bandwidth and absorption peak to furan concentration.....	64

**LIST OF TABLES**

Table 1-I: Summary of primary causes of transformer failures .....	3
Table 3-I: Six test samples prepared for laboratory accelerated aging process .....	25
Table 3-II Diluted samples from different original furan concentration.....	38
Table 3-III: Selected oil samples' test result by GC/MS .....	42
Table 3-IV Bandwidth length and absorption peak at different furans content level	46
Table 3-V Slight variation in absorption bandwidth and maximum absorption.....	50
Table 4-I Comparison between simulation and field measurement result.....	65
Table 4-II Comparison between ASTM D 5837 and UV-Vis Spectroscopy with Fuzzy Logic.....	67
Table 5-I: Key Contribution of novel UV-Vis spectroscopy and Fuzzy Logic analysis .....	70

**ABBREVIATIONS**

Abbreviation	Definition
2-ACF	2-Acetyl-furan
2-FAL	2-Furan
2-FOL	2-Furfurol
5-HMF	5-Hydroxy methyl-2-furfural
5-MEF	5-Methyl-2-furfural
ASTM	American Society for Testing and Materials
DGA	Dissolved Gas Analysis
DP	Degree of Polymerization
FTIR	Fourier Transforms Infra-Red
GC/MS	Gas Chromatography-Mass Spectrometry
HPLC	High-Performance Liquid Chromatography
IEC	International Electrotechnical Commission
LG	levoglucosane
NIR	Near Infra-Red
UV-Vis	Ultraviolet-to-Visible

**SYMBOLS**

Symbols	Units	Definition
$A_\lambda$		Absorption Index
$S_\lambda$		Sample intensity at wavelength $\lambda$
$D_\lambda$		Dark intensity at wavelength $\lambda$
$R_\lambda$		Reference intensity at wavelength $\lambda$
$\lambda$	nm	Wavelength
ppm		Parts per million
	g	Gram
	°C	Celsius

# 1 INTRODUCTION

## 1.1 Power Transformer



**Figure 1-1 Power transformer, front view**

Large oil-filled electrical power equipment, such as the power transformer shown in Figure 1-1, is a critical element in an electrical power system. Power transformer is utilized to raise or lower the voltage level as needed to serve the transmission or distribution networks. Through the use of device such as the transformer, AC electric power is generated at one central location. Its voltage stepped up for transmission over long distances at very low losses, and then stepped down for final use. Once it steps up the voltage level of a circuit, it decreases the current to keep a constant power balance. Since the transmission losses in transmission lines are proportional to the square of the current, raising the transmission voltage and reducing the resulting transmission current by a factor of 10, it reduces power transmission losses by a factor of 100 [1]. Power transformer plays the key role in preserving efficiency and in maintaining continuous transmission of power in the grids. Power transformers rate from few kilowatts to hundred megawatts, and substantially weight over hundreds of tons. The price of a single power transformer ranges from 50 thousand to five million of dollars. It is one of the most expensive asset in power transmission and distribution networks that is crucial to the profitability of electrical utilities company. Million of dollars are spent each year in operating, maintaining and repairing this equipment. Without the transformer, it would be impossible for the modern society to use electric power in many of the ways it is used today.

## 1.2 Power Transformer Failures



**Figure 1-2: Picture of transformer explosion**

The reliability and continuous performance of the power transformer is one of the vital key to profitable power generation and transmission. However, due to the practice of minimizing the capital expenditures of electrical power system, it is very common to operate these equipments close to the limits of their design such as with the maximum load capability. The cost of acquisition, replacement, transportation, installation and repairs of power transformer is among the highest cost in the system. Its failures will create losses of revenue and if catastrophic, there will be substantial costs in terms of the destruction of the connected equipment, environmental damage, and unexpected use of resources.

Over the decades, transformer failures have been common and costly. Transformers are considered by Corporate Risk Managers and Insurers as the most critical equipment inside plants because of the large quantity of oil in contact with high voltage elements [2]. According to the statistics done over a one year period, it was discovered that 730 transformer explosions happened in the USA in the year 2001 alone [2]. Many experts anticipate that the number of failures will increase significantly in the near future, from 1% in 2001 to 2% in 2008. As depicted in Figure 1-2 [2], an example of transformer explosion due to insulation failure is illustrated. Table 1-I[2] summarizes the primary causes of transformer failures according to the investigation, carried out over the last several decades by Hartford Steam Boiler Insurance Company (HSB). The table shows the areas where failure-

reducing efforts can best be directed. Insulation deterioration, which was the second leading cause of failure in the most recent studies, has clearly shown the significance of its contribution in transformer failure. The average age of the transformers that fail due to insulation deterioration is 17.8 years. This is too far from the expected normal life which ranges from 35 to 40 years as quoted in [2]. Therefore, insulation strength within the transformer plays a key role in affecting its life expectancy. Of all the common causes of transformer failure, insulation strength deterioration is one that can be continuously monitored. And through this continuous monitoring, transformer failure could have been avoided.

**Table 1-I: Summary of primary causes of transformer failures**

<b>Common causes of transformer failure</b>	<b>1975</b>	<b>1983</b>	<b>1998</b>
Lighting Surges	32.3%	30.2%	12.4%
Line Surges/External Short Circuit	13.6%	18.6%	21.5%
Poor Workmanship Manufacturer	10.6%	7.2%	2.9%
Deterioration of Insulation	10.4%	8.7%	<b>13%</b>
Overloading	7.7%	3.2%	2.4%
Moisture	7.2%	6.9%	6.3%
Inadequate Maintenance	6.6%	13.1%	11.3%
Sabotage, Malicious Mischief	2.6%	1.7%	0
Loose Connections	2.1%	2.0%	6%
All Others	6.9%	8.4%	24.2%

### **1.3 Difficulties with Power Transformer Insulation Strength**

#### **Assessment**

Current practicing engineers use a number of modern diagnostic techniques to assess the insulation condition of aged transformers. These techniques are categorized into electrical and chemical analysis. Electrical analysis such as:

- Partial discharge (PD) analysis [3]
- Dielectric breakdown voltage measurement [4]
- Return voltage measurement [5]

- Time domain polarization measurement [6]
- Frequency domain polarization measurement [6]

Chemical analysis such as:

- Moisture analysis in transformer oil by Karl Fischer titration [7]
- Dissolved gas analysis (DGA) [8]
- Degree of polymerisation (DP) measurement [9]
- Furan analysis by high performance liquid chromatography (HPLC) [10].

Of the entire insulation strength diagnostic techniques, furan analysis is the focus of this research project. Recently, furan analysis has become more popular in the field of transformer insulation strength assessment and transformer remnant life estimation related research. ASTM D5837 is the current widely accepted standard test method of furan measurement as published by American Society for Testing and Materials (ASTM) [10]. This test is reliable and accurate in identifying and measuring the concentration of furfural derivatives in transformer oil. However, the test performed under this standard has a few disadvantageous as summarized below:

- The test is time consuming and laborious.
- Professional skills are required to perform the test because of its complexity.
- Test equipments and apparatus are expensive.
- Increases the cost of asset management as electrical utilities company employs oil analysis companies to perform the furan analysis.
- Delays in getting test result due to possibility of large number of test samples from other companies in the queue.

The main objective of this research is to develop an alternative method in measuring furan derivatives concentration available in transformer oil. This outcome of this research is beneficial to the electrical power engineering industry especially in the asset management field. At the completion of the project, the developed method is simple, which allows engineers to conduct condition assessment test on power transformer without the need to acquire any specific skills; thus, reducing the cost of the test. This project had been in collaboration between university and several infrastructure industry parties.

## **1.4 Research Objectives**

The main objectives and contributions of this research are:

1. To investigate the correlation between furan concentration and UV-Vis spectral response using absorption test.
2. To investigate the UV-Vis spectral response of the oil under different environmental conditions.
3. To develop a method to estimate furan concentration based on UV-Vis spectral response.
4. To develop an alternative method in furan measurement that could replace ASTM D 5837.

## **1.5 Organization of the Thesis**

There are five chapters and one appendix in this thesis. Brief description of the contents for the rest of the chapters is as follows:

In Chapter 2, a literature review of the topics related to power transformer insulation is presented. The mechanism of insulation degradation occurred in power transformer insulation system is discussed in this chapter. An overview of the current electrical and chemical diagnostic methods in assessing the insulation condition is also presented in this chapter. In addition, new emerging insulation diagnostic method by spectroscopy analysis is also discussed. It concludes with a detail analysis of furanic compounds in transformer oil.

Chapter 3 presents the description of the experimental works and result. Details on how the experiment is done and the standards used to ensure the quality of the work is explained in this chapter. The experiments consist of a series of tests that are done based on the conventional method as well as the newly designed method. Analysis and discussion based on the result obtained from the experiment are presented, as well as comparison between the result from the conventional method and the newly developed method. This is done to investigate their correlation relationship. The validity on the result at other ambient temperature condition was also studied and presented in this chapter.

Chapter 4 is intended to give an overview of the Fuzzy Logic theory used in predicting the furan concentration based on the UV-Vis spectral response from the oil sample. A definition of Fuzzy Logic is firstly provided, followed by the method used to interpret the result from the experiment into the simulation model that was designed in MATLAB platform. A verification of the estimation result from the simulation model with the experimental result is then supplied. The possibility of using the UV-Vis spectroscopy incorporated with Fuzzy Logic model as an alternative to the current method of furan measurement standard, ASTM D5837, is also discussed in this chapter.

In Chapter 5, conclusion and recommendation on the future of the research are presented. The thesis is concluded with the explanation on the significance of the work done.

## 2 POWER TRANSFORMER INSULATION

### 2.1 Introduction



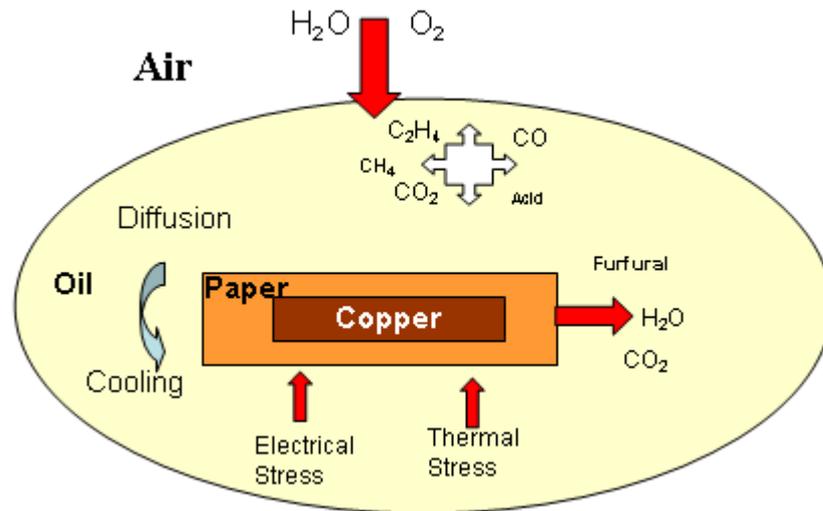
**Figure 2-1: Three-phase oil-cooled transformer with cover cut away.**

In contrast to small transformers, which can be practically self-cooled by air circulation, large power transformers are usually immersed in transformer oil that cools and insulates the windings [11]. An example of a three-phase oil-cooled transformer with the cover cut away is shown in Figure 2-1 [12]. The oil reservoir for the transformer in the figure is visible at the top. Due to high temperature operating conditions, large power transformer windings are immersed in transformer oil that acts as a cooling medium and helps in reducing corona discharge. Power transformer windings are insulated with multiple layers of Kraft paper and immersed in mineral oil. The paper insulation is required to withstand both electrical and mechanical stress. The paper and oil insulation degrades over time at a rate depends on the operating temperature, moisture level, and oxygen present in the oil [13, 14]. The degradation of original properties and the production of by-products are stimulated in the deterioration process. The quantity of these derivatives and the degree of changes in properties are used to gauge the insulation condition in the power system [15].

Over the decades, various condition monitoring methods were developed by organizations and research institutes by which to investigate transformer insulation condition. These methods are generally classified into electrical and chemical analysis. They are available as a standard guideline published by ASTM and International Electrotechnical Commission (IEC) organizations. These organizations have made significant contributions in the advancement of technology and skills for diagnostic techniques. Their standards are revised and updated from time to time to keep in touch with the current situation. Researchers and engineers around the globe are constantly searching, modifying, and developing new methods for condition diagnostic of electrical equipment in electrical utilities. The purpose is to seek advancements in technology to provide better, more effective, accurate, and economic approaches to or inventions in condition monitoring and diagnostic methods.

## **2.2 Deterioration Mechanisms in Transformer Insulation**

Liquid insulation is a type of mineral oil made by refining a fraction of the hydrocarbons collected during the distillation of a petroleum crude stock [16]. The basic requirement of this mineral oil has to be in agreements with standard specifications developed by groups of experts such as ASTM Standard Specification D3487 [17] and International Electrotechnical Commission (IEC) Specification 296 [16]. These are guidelines for the acceptable mineral insulating oil characteristics for new transformer oil. Mineral insulating oils are complex mixtures of many individual hydrocarbon compounds, and the relative amounts of these hydrocarbons can be different in crude oil that comes from different sources. Generally, these hydrocarbon compounds are members of three classes such as alkanes, naphthenes, and aromatic hydrocarbons [16]. As a result of malfunction, gases such as hydrogen ( $H_2$ ), methane ( $CH_4$ ), acetylene ( $C_2H_2$ ), ethylene ( $C_2H_4$ ), ethane ( $C_2H_6$ ), propane ( $C_3H_8$ ) and butane ( $C_4H_{10}$ ) are generated as a result of the decomposition of insulating oil [18].



**Figure 2-2 Schematic diagram of insulation system and deterioration mechanism inside a transformer**

The main constituents of Kraft paper are cellulose (90%), lignin (6-7%), hemicelluloses or pentosans (3-4%), traces of metallic cations and also absorbed water (typically 2-4% water/paper weight ratio) [19, 20]. Degradation of paper is strongly influenced by scission and shortening of cellulose chain [21]. The cellulose is depolymerized by a succession of chemical reactions that cause chain scissions and the release of gases and water into the surrounding oil, and some larger molecules such as furfurals [22]. The overall deterioration mechanism inside a transformer insulation system is illustrated in Figure 2-2 [23].

### 2.3 Diagnostic Techniques in Power Transformer Insulation

A power transformer insulation system consists of solid (paper) and liquid (insulating oil) insulation. Their insulation strength degrades over a period of time depending on transformer loading and the surrounding environment condition. The characteristics of by-product generation and changes in properties provide a good indication of the insulation condition of the transformer. Sudden increases or drastic changes in these by-products provide substantial warning to engineers for necessary actions needed to avoid any disastrous consequences. The techniques in monitoring these phenomena are mainly governed by the standards published by ASTM and IEC. The diagnostic methods of insulation degradation are categorized into electrical and chemical analysis.

### 2.3.1 Electrical Diagnostic Techniques

Electrical diagnostic techniques for condition monitoring or for studying the degradation of electrical insulation in power transformers are relatively new [6]. Partial discharge (PD) is an electrical phenomenon that occurs inside a transformer and the magnitude of its discharge could cause progressive deterioration and lead to insulation failure [6]. There are a number of PD measurement guidelines available in ASTM. One of them is ASTM D1868 [4] (test method for detection and measurement of partial discharge pulses in evaluation of insulation system). It is a specific guideline for the detection and measurement of PD (corona) pulses at the terminals of an insulation system under an applied test voltage, including the determination of PD (corona) inception and extinction voltages as the test voltage is raised and lowered [3]. It is also used for determining quantities such as apparent charge and pulse repetition rate together with such integrated quantities as average current, quadratic rate and power, which are essential in the design and inspection of molded, laminated, and composite insulation of power transformers [3]. Because the presence of partial discharges (corona) in an apparently solid insulation may be an indication of the existence of internal cavities, which may lead to disastrous consequences [3].

Dielectric breakdown voltage measurement of insulating oil is another electrical diagnostic method that is commonly used for transformer insulation assessment [4, 5, 24-26]. ASTM D1816 [4] is the standard method that has been used in diagnostic and laboratory investigations of the dielectric breakdown strength of oil in insulating system. Dielectric breakdown voltage measures the ability of the liquid to withstand electric stress without failure. Low breakdown voltage indicates the presence of contaminating agents such as water, dirt, cellulosic fibers, or conducting particles in liquids [4]. There are other electrical diagnostic methods that test the dissipation factor (or power factor) in new electrical insulating liquids and in-service transformer oil [4, 26].

Saha [6] had provided a significant contribution in reviewing the modern electrical diagnostic techniques for insulation condition assessment in transformers. In recent years new diagnostic methods have been promoted, complementary to the classical

PD, dielectric breakdown voltage and dissipation factor measurement [6]. Only some of these methods are covered briefly in this section, amongst which are time domain polarization and frequency domain polarization measurement as published in [6]. Insulation assessment by time domain polarization measurement is achieved by calculating the response function of a return voltage from a dielectric that is charged with DC voltage for a long period of time. Osvath et al [27] stated that the smaller the time taken to reach the return voltage peak value, the worse is the insulation condition of the transformer. On the other hand, frequency domain analysis uses AC voltage and measuring on the dissipation factor as a function of the frequency of the AC voltage [6]. Gafvert et al. [28] compared the result from time domain and frequency domain measurements. He reported that the former one is useful but sensitive to systematic errors while the latter is the better for fieldwork [28].

The report published by CIGRE Task Force 15.01.09[29] highlights the importance and problems in the interpretation of results from return voltage, time and frequency domain polarization measurement. It stated that the influence of oil gap (condition of oil conductivity) has a significant impact on the dielectric response which should be taken into consideration while attempting to diagnose the moisture level of solid insulation [29].

### 2.3.2 Chemical Diagnostic Techniques

Chemical diagnostic techniques have important roles in the current trend of power transformer insulation assessment. Referring to Figure 2-1 [23], insulation system deterioration inside a transformer causes the degradation in tensile strength of the insulating paper and the production of water, gases, and furan derivatives (organic compounds)[23]. C57-106 [15] of IEEE highlights the significance of oil characteristics in affecting the overall reliability of the transformer performance. It also outlines the standard test methods that should be used in detecting these by-products, such as moisture analysis by ASTM D1533 [30], dissolved gas analysis (DGA) by ASTM D3612 [8], and furan derivatives measurement by high performance-liquid chromatography (HPLC) in ASTM D5837 [10]. In addition, tensile strength of the paper is monitored by using degree of polymerization (DP) measurement in ASTM D4243 [9].

Electrical characteristics of new or used insulating oil are the major concern in insulation strength monitoring. Its characteristic are affected by excessive water content [30]. High level of water content renders the insulating oil unsuitable for use in a power transformer due to the deterioration of its dielectric strength - such as lower dielectric breakdown voltage [4]. The use of ASTM D1533 [30] that utilizes the method of Karl Fischer titration techniques is the current practice of assessing moisture level in transformer oil.

DGA by ASTM D3612 [8] is accepted worldwide as another technique for the detection of incipient insulation faults. Insulating oil and oil-immersed insulation materials decompose under the influence of thermal and electrical stresses, and therefore, generate gaseous decomposition products of varying composition which dissolve in the oil [8]. The amount of each individual is used to indicate the type and degree of the abnormality [8]. The gases of interest are [6]:

1. Hydrocarbon gases and hydrogen: CH<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>2</sub>, C<sub>3</sub>H<sub>8</sub>, C<sub>4</sub>H<sub>10</sub> and H<sub>2</sub>
2. Carbon oxides: carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>)

Emsley et al [21] discovered that a healthy transformer has less than 0.05ml of hydrocarbon gases per 100ml of oil. Detailed analysis on interpretation of gas-in-oil analysis using IEC 60599 and IEC TC 10 databases is available in [31]. Generally, a surge of these gases is normally caused by [21]:

1. Corona or partial discharge
2. Thermal heating
3. Arcing

Current techniques of insulating paper strength diagnostic are mainly by DP measurement using ASTM D4243 [9] and furan analysis by HPLC using ASTM D5837 [10]. Transformer paper is a sheet of material made from organic cellulose, which consists of 90% wood cellulose, 7% lignin and 3% hemicelluloses [23]. In ASTM D4243 [9], the quality of the cellulose is measured by determining the average viscometric DP of the new or aged transformer paper. DP measurement is also defined as the measurement of the average number of glucose monomer units

available in the cellulosic paper. Due to the impracticability of collecting paper samples from an operating power transformer, furan analysis by HPLC using ASTM D5837[10] is an alternative for solid insulation assessment in power transformers. Furanic compounds are oil soluble derivatives from the degradation of cellulosic materials used in the insulation systems. By using HPLC equipped with a suitable analytical column and UV detector, a high concentration of furan measurement indicates serious cellulose degradation caused by aging or incipient fault conditions [10]. Also, the result from this test can be considered complementary to the test result from DGA.

## 2.4 New Diagnostic Methods by Spectroscopy Analysis

In recent years, new diagnostic methods have been developed that are complementary to the classical insulation strength measurement. These methods are Infrared (IR) [32-34], Near-infrared (NIR) [35, 36], and Ultraviolet to Visible (UV-Vis) [37, 38] spectroscopy analysis. These methods are based on light absorbance and reflectance tests at certain wavelengths to determine the acceptable and unacceptable sample of oil. The major advantages of this method are its non-destructive and non-consumable characteristic to the examined sample [6].

Blue et al [32] developed an alternative technique involving IR analysis to measure by products of paper degradation present within the oil. He also reported on the possibility of installing a miniaturized IR spectrometric unit to a transformer that could continuously monitor the transformer oil in the field, thus providing earlier warning of problems resulting from paper degradation [32]. Percherancier et al [33] used more advanced IR technology, Fourier Transformer-IR (FT-IR), for better sensitivity detection of additives or undesirable impurities at low content (<100ppm) without preliminary extraction. He developed a spectra accumulation technique combined with a spectra subtraction technique in conjunction with a collection of pure compound spectra as a data base and improved the detection limit by a factor of seven [33]. Itahashi et al [34] used Fourier FT-IR to monitor the conductivity of the oil, based not only the amount of water in the transformer oil, but also on the state of the water. By using FT-IR spectral analysis, he investigated the difference in

conduction phenomena depending on whether the water is free or combined with the polar structure of the hydrocarbon based insulating liquid [34].

Neimanis et al [35] developed a technique for determining moisture content in oil impregnated paper using NIR spectroscopy analysis. The author showed that NIR spectroscopy method with multivariate modeling can produce accurate results in measuring moisture content and the possibility of replacing the conventional method [35]. Shenton et al [36] reported that NIR coupled with chemometrics analysis, is capable of providing physical property data that is useful in assessing the condition of transformer insulation materials. The author found that NIR analysis is sensitive to aromatic C-H functionalities content of mineral oils and has the potential to provide easier and more cost effective methods in assessing physical property of transformer insulation [36].

Palmer et al [39] found that the transformer oil absorbance increases by a significant and easily observable margin over the range of UV-Vis wavelengths. The absorbance characteristic study was done on in-service and laboratory aged transformer oil. Figure 2-3 [39] is the region found in the UV range where correlation is exhibited between UV absorption test and samples oil collected from the industry. Among the samples used, 1 and 2 are in-service oil that fulfil the specification for in-service insulation. Used oils 3 to 8 are in-service oil that failed to meet the specification. Based on the correlation between transformer oil aging and its UV spectral response, the author propose a prototype system that consists of light source, filter, guide and detection components, and simple computational function, for the purpose of future field monitoring of transformer oil aging [39]. Similar results of aged transformer oil absorption tests in the UV-Vis range was also investigated by Arshad [38].

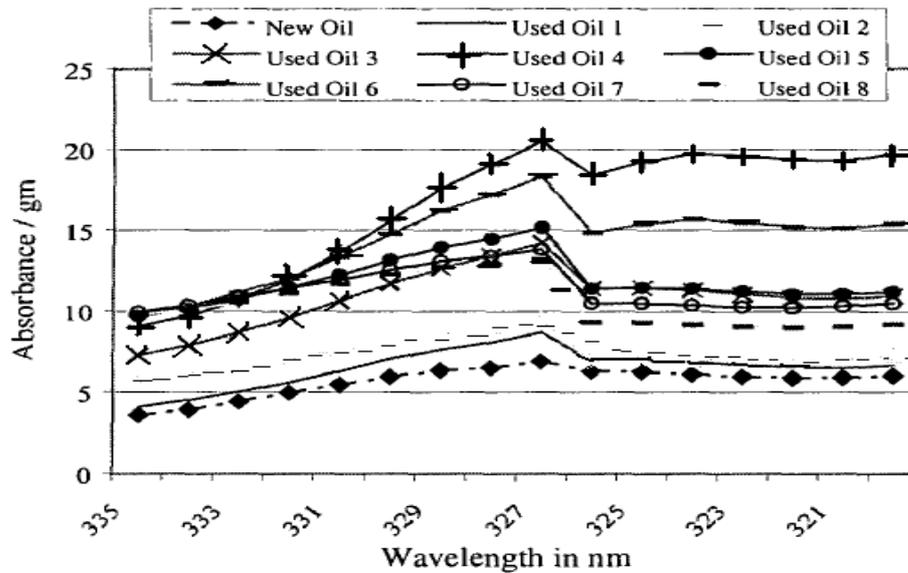
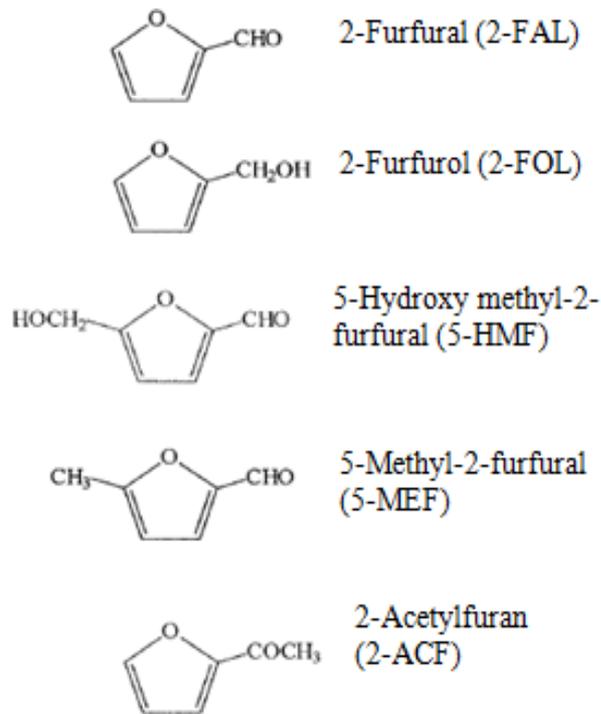


Figure 2-3: Degradation correlation in 320-335nm

## 2.5 Furanic Compounds in Transformer Oil

Furfural analysis is gaining popularity in the recent trend of transformer insulation strength assessment, transformer remnant life estimation or related research field. This is due to its direct connection with the solid insulation strength in the power transformer system. ASTM D5837[10] is the widely used standard method in detecting furan derivatives using HPLC equipments or gas chromatography-mass spectrometry (GC/MS) equipment, which is also used by the experts in the industries [18]. The detectable furanic compounds in transformer oil with the current available technology are 2-furan (2-FAL), 2-Furfurol (2-FOL), 5-Hydroxy methyl-2-furfural (5-HMF), 5-Methyl-2- furfural (5-MEF), and 2-Acetylfuran (2-ACF) shown in Figure 2-4 [22].

Although it has been known for some time that the hydrolytic degradation of cellulose can lead to the formation of furanic compounds, particularly 2-FAL, the mechanism by which this occurs is still unclear [22]. However, it is proposed that furans are produced from pyrolysis mechanism of levoglucosane (LG) and hydrolytic degradation of cellulose in the paper [13]. LG, the precursor of furanic compounds, is the by-product due to thermal degradation of cellulosic paper at temperatures higher than 130°C [13].



**Figure 2-4 Furanic compounds detectable in transformer oil that has been in contact with degraded cellulosic insulation**

It was reported by Scheirs et al [22] that LG leads to the production of all five types of furan derivatives as illustrated in Figure 2-5 [22]. The work implies that furans are generated in the case of an abnormal hot spot inside the transformer. In addition, hydrolytic thermal degradation that contributes to the chain scission of cellulose is also an important factor of furanic derivatives generation at normal operating temperature of 80-120°C shown in Figure 2-6 [40]. Technically, furans are also generated in transformer oil during normal operating temperature due to the existence of moisture in the paper and air that leads to oxidative hydrolysis of the cellulose. As the hydrolytic mechanism of the degradation of solid insulation requires a lower activation energy than the pyrolysis mechanism, Hohlein [13] had proven that hydrolysis degradation mechanism is the major contributor for 2-FAL in transformer insulating oil at normal service temperature. This finding explains the on-site observation, which found that wet transformers have higher levels of furans, inferior oil properties, and lower DP values of paper than dry transformers that are under the same service conditions [13].

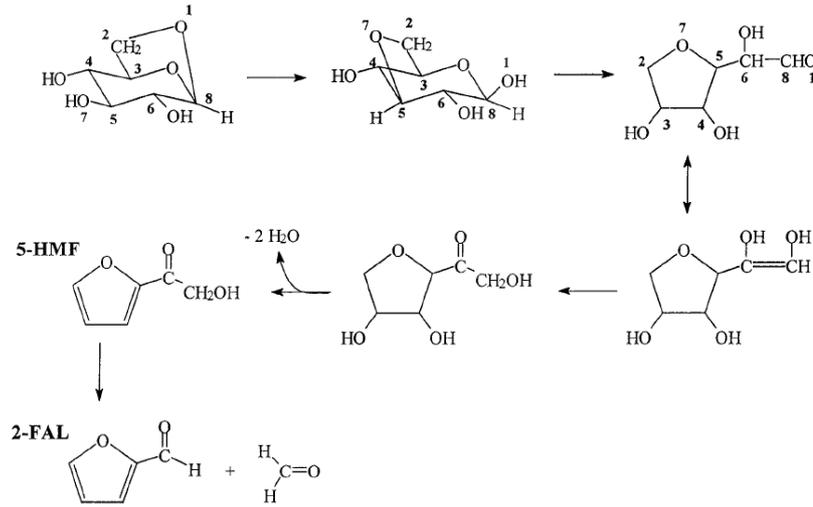


Figure 2-5 Production of 5-HMF and 2-FAL from LG

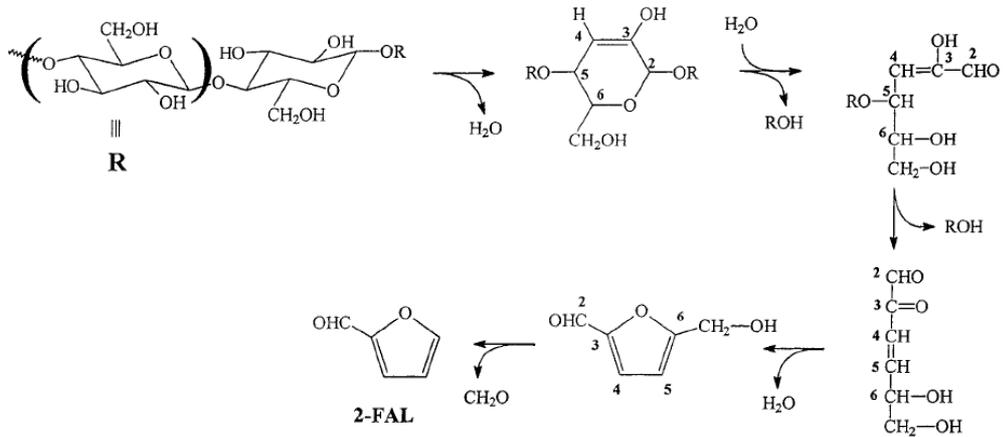


Figure 2-6 Production of 5-HMF and 2-FAL from hydrolytic thermal degradation of cellulose; R represents the cellulose chain

The rate of furanic compounds production with respect to insulating oil temperature is investigated by Sergei Levhik et al. [41]. Under laboratory-controlled condition with accelerated ageing method based on heating rate of 1°C/h, the amount of furanic compounds detected in oil containing paper as a function of temperature is depicted in Figure 2-7 [41]. It shows that furans production surge at temperature beyond 150°C and their concentration is dominated by 2-FAL, which is consistent with furan measurements in operating transformers [41]. The amount of furanic compounds detected in the Kraft paper immersed in the sample oil is depicted in Figure 2-8 [41]. It shows the similar trend of furanic compounds production at temperature beyond 150°C but with 5-HMF is the highest concentration. The result indicates that 2-FAL has the highest solubility in oil among all furans [41].

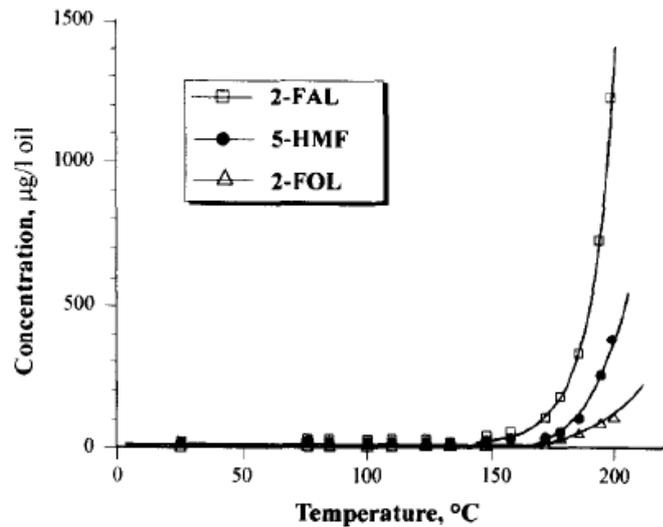


Figure 2-7: Furanic compounds detected in oil containing paper as a function of temperature

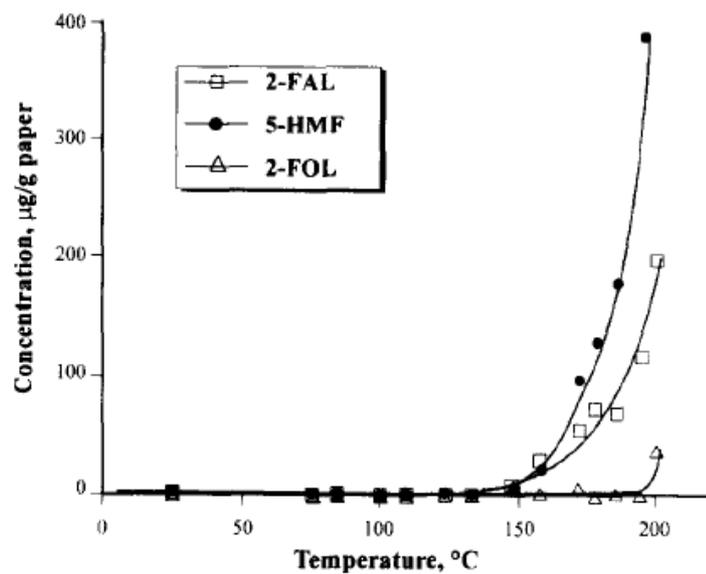


Figure 2-8: Furanic compounds detected in Kraft paper as a function of temperature

At normal transformer operating temperature such as 85°C, furanic compounds are still generated as described in Figure 2-9 [14]. Kachler et al [14] found that the main furan derivative is 2-FAL and oxygen has a significant effect on the production of furanic compounds. Hohlein et al [13] investigated the correlation between 2-FAL and DP measurement at 75C, 85C and 95C, plotted in Figure 2-10 [13]. It proves that furan measurement is an integral to the DP condition of the cellulosic paper. Furthermore, according to the large-scale survey of furanic compounds in operating transformers done by John [42] in USA, the furan compounds in operating transformer oil are mainly constituted by 2-FAL. Therefore, it is possible to use 2-FAL only as a cellulosic insulation degradation indicator.

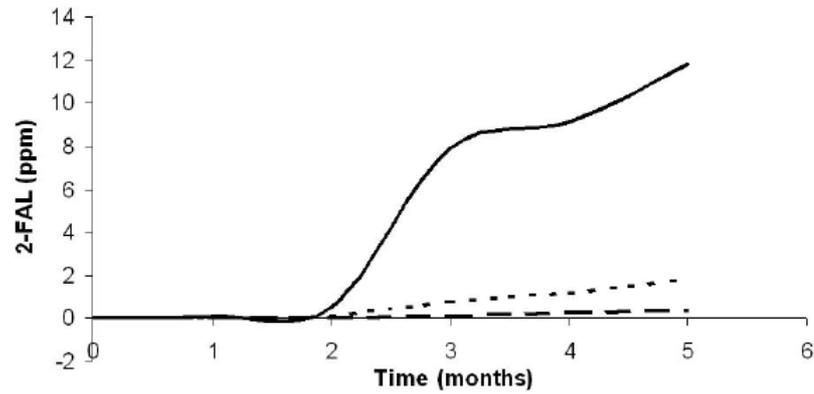


Figure 2-9: Development of 2-FAL with time at temperature of 85°C. (solid line - air & oil A, dotted line - air & oil B, dashed line - oil A only)

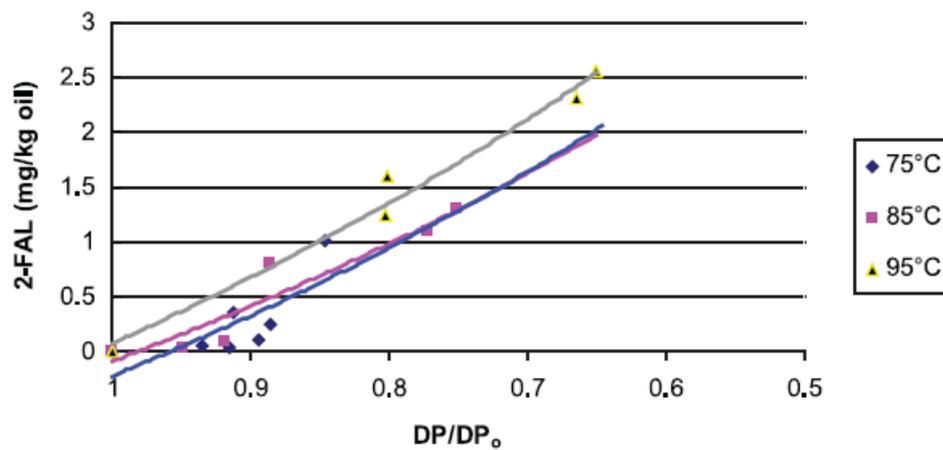


Figure 2-10: Correlation of 2-FAL with DP in dried pressboard at different aging temperatures ( $DP_0$  is the initial DP value of pressboard prior to aging)

De Pablo [43] reported on the correlation between furfural and  $DP$  as described in equation 2-1 [43]:

$$DP = \frac{7100}{8.88 + 2FAL} \quad (2-1)$$

where 2-FAL is expressed in ppm of oil.

Transformer oil furan analysis plays an essential part in transformer health condition monitoring. Furans are generated in the case of an abnormal hot spot inside the transformer and a high concentration of these compounds indicates that the transformer might have reached the end of its life of operation [9, 13]. The result is also a complement to DGA; providing more data in transformer remnant life estimation. In other words, a regular monitoring of furans concentration available in transformer oil can avoid incipient faults.

## **2.6 Summary**

This chapter covers an intensive literature review on the topics related to power transformer insulation. The mechanism of power transformer insulation degradation is given. Mainly, insulation deterioration is driven by heat, moisture and air in the power transformer system. There are different standard of diagnostic method published by ASTM and IEC in monitoring these insulation degradation level. These standards are generally categorized into electrical and chemical diagnostic technique. There are new diagnostic methods emerging provide alternative techniques in assessing the insulation strength by using spectroscopy analysis. The chapter concluded with the details from investigations into furan compounds generation in insulating oil analysis.

## 3 EXPERIMENT AND RESULTS

### 3.1 Introduction

This chapter covers the details of the experimental work done in investigating the correlation between furan concentrations in transformer oil with its UV-Vis range spectral response analysis. Series of tests were conducted on short-term laboratory accelerated aged and in-service transformer oil by using GC/MS and UV-Vis spectroscopy. The experimental work was done in collaboration with the industry who provided the chemical testing facilities required for the furan test by ASTM D5837 (modified) [10]. The experimental work in the research was conducted with ongoing supervision and consultation from experts in the industry.

In keeping with the concept of project practicability in the relevant engineering industry, the laboratory works were planned and performed with reference to the standards of:

- ASTM D3487 Standard Specification for Mineral Insulating Oil used in Electrical Apparatus [17]
- IEC 61125 Unused Hydrocarbon-based Insulating Liquids-test Method for Evaluating the Oxidation Stability[44]
- ASTM D923 Standard Practices for Furanic Compounds in Electrical Sampling Electrical Insulating Liquids [45]
- ASTM D5837 Standard Test Method for Furanic Compounds in Electrical Insulating Liquids by High-Performance Liquid Chromatography (HPLC) [10]
- ASTM E275 Standard Practice for Describing and Measuring Performance of Ultraviolet, Visible, and Near-Infrared Spectrophotometers [46].

The correlation between furan concentration in oil and UV-Vis spectral response is investigated. Results show that furan concentration in transformer oil is almost linearly correlated with the spectral response bandwidth and absorption peaks in the UV-Vis range wavelength. With respect to this characteristic, a convenient, economical and accurate method of furan content in oil measurement is developed.

## 3.2 Experimental Work

### 3.2.1 IEC 61125 Unused Hydrocarbon-based Insulating Liquids-test Methods for Evaluating the Oxidation Stability

IEC 61125 is a standard prepared by International Electrotechnical Commission (IEC) Technical Committee No. 10: Fluids for electro-technical application [47]. It is a standard that describes three test methods (using the same apparatus) for evaluating the oxidation stability of mineral insulating oils and hydrocarbon-based insulating liquids. The three methods comprise oxidation stability evaluation of [47]

- Unused uninhibited mineral insulating oils under accelerated conditions
- Unused inhibited mineral insulating oils under accelerated conditions
- Unused uninhibited and inhibited hydrocarbon insulating liquids under accelerated conditions

The general principle of the method as stated in the standard is that the liquid sample to be tested (through which a stream of oxygen or air is bubbled), is maintained for a given period at a given temperature, 100°C or 120°C, in the presence of solid copper [47]. The resistance to oxidation is evaluated from the amount of total sludge and total acidity formed or from the time to develop a given amount of volatile acidity.

The reason this standard is used for the research is not for the purpose of evaluating the resistance to oxidation of the oil, but to utilize the way of accelerated aging process on the oil. In other words, laboratory aged transformer oil for furan testing is prepared by using the heating process given in the standard.

Selected equipments used in the experiments are:

- 1) Heating arrangement
  - a. A thermostatically-controlled aluminum alloy block heater was used to maintain the insulating liquid in the desired number of oxidation tubes at the required temperature  $100^{\circ}\text{C}\pm 0.5^{\circ}\text{C}$  as shown in Figure 3-1 [47]. The oxidation tubes were inserted into the holes to an overall depth of 150mm. During the heating, equipment was protected from direct sunlight and air draughts.

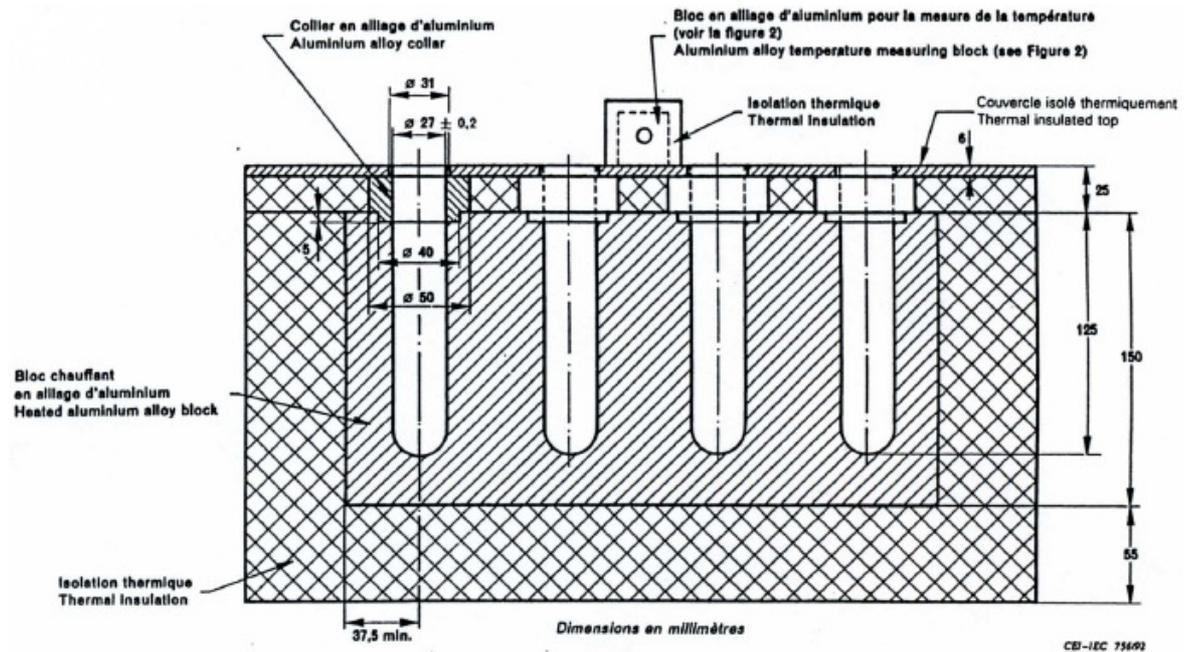


Figure 3-1: Sample of heating block with 8 holes

## 2) Test vessels

a. Test tubes of neutral glass provided with a 24/29 ground joint of the following dimensions were used:

- |                        |           |
|------------------------|-----------|
| i. Overall length      | 210±2mm   |
| ii. External diameter  | 26±0.5mm  |
| iii. Wall thickness    | 1.4±0.2mm |
| iv. Height of the head | 28±2mm    |
| v. External diameter   | 5.0±0.4mm |
| vi. Wall thickness     | 0.8±0.1mm |

b. Sample test tube as according to the standard is shown in Figure 3-2 [47].

## 3) Absorption tubes

a. These were identical to the test vessels and the distance between the axes of the two tubes was 150mm±50mm. Connections between the test and absorption tubes were position as close as possible. These tubes were mounted outside the heating device. Sample connection of tubes is as illustrated in Figure 3-3 [47].

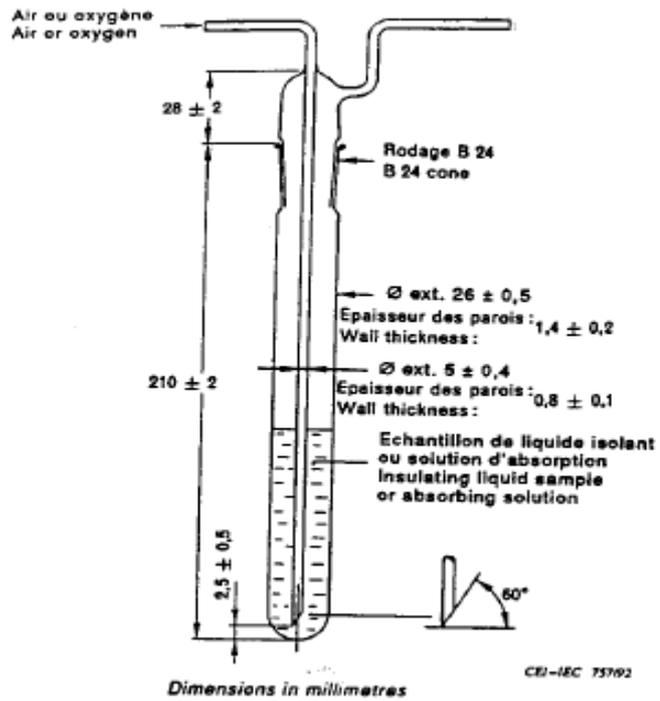


Figure 3-2: Sample of test tube used as according to the standard

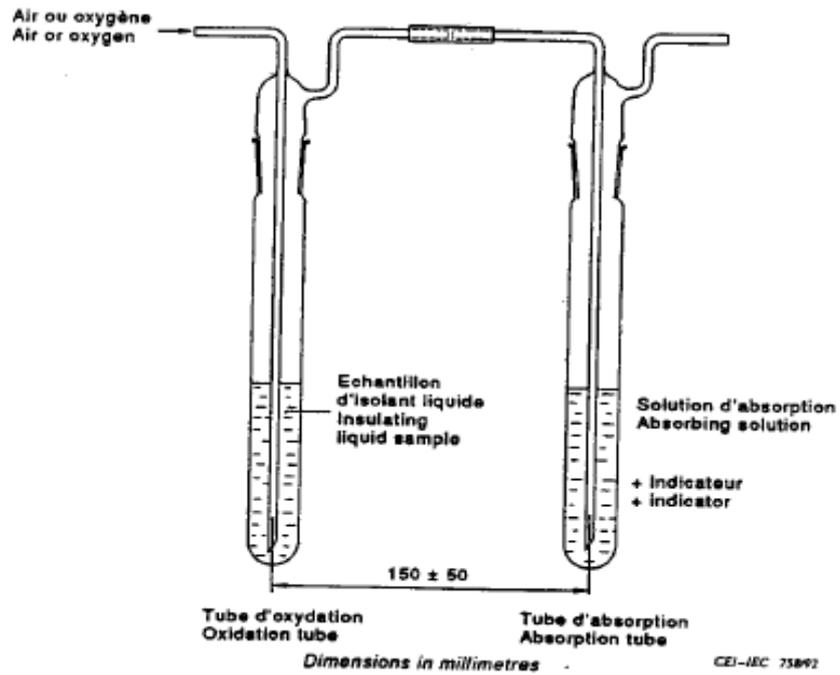


Figure 3-3: Oxidation tube and absorption tube assembly

4) Gas supply

- a. Gas (oxygen) from a compressed gas cylinder, was dried by passing through a scrubber bottle containing concentrated sulphuric acid and then through a tower filled with alternate layers of glass wool and soda lime.

Cleaning of all test vessels is very important as test samples should be protected from any other contaminants. The test and absorption tubes were chemically cleaned by washing with acetone followed by distilled or deionized water. The tubes were then dried in an air oven at 105°C for 3 hours. Dried tubes were then allowed to cool to room temperature in a desiccator or dry cabinet in which they were kept ready to be used.

Catalysts used in the experiment were:

1) Copper strips

- a. Each copper strip used as an aging catalyst had thickness less than 2mm, 4mm width and length ranging from 40mm to 10mm.
- b. New transformer (Kraft) paper with 20mm width and 280mm length to wrap around the copper strip.

Each copper strip wrapped with transformer paper was impregnated in 25g of new transformer oil. The new transformer oil used in the experiment was Shell Diala B. It is a commonly used transformer oil that meets the physical, electrical, and chemical properties specification in ASTM D3487 [17] (Mineral Insulating Oil used in Electrical Apparatus). There were six test samples prepared for the process of laboratory accelerated aging. For the purpose of accuracy, transformer oil and the catalysts were weighted according to the values as shown in Table 3-I:

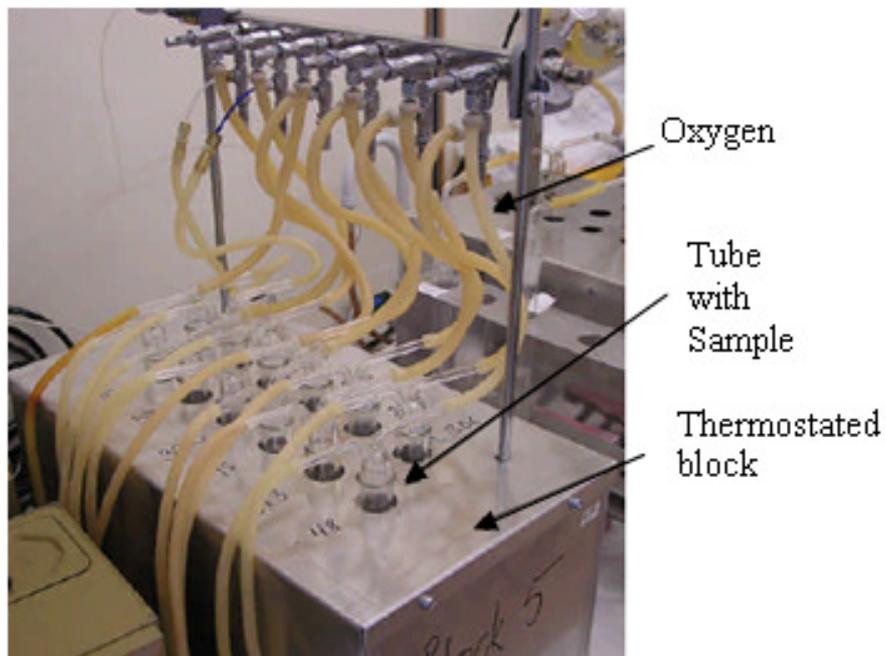
**Table 3-I: Six test samples prepared for laboratory accelerated aging process**

<b>Test Sample</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>
New transformer oil (g)	25	25	25	25	25	25
Copper strip (g)	0.8	1.0	1.2	1.4	1.6	1.8
Transformer paper (g)	0.8	1.0	1.2	1.4	1.6	1.8

Laboratory accelerated aging process was done by using the equipment as discussed in the previous paragraphs. The heating temperature was set at 100°C, continuously for 7 days. Test sample prepared was as shown in Figure 3-4. Sample picture of laboratory accelerated aging assembly following the standard of IEC 61125 [47] is as illustrated in Figure 3-5.



**Figure 3-4** Test sample consist of copper strip wrapped with transformer paper impregnated in a 25g of new transformer oil.



**Figure 3-5** Laboratory aging transformer oil assembly in compliance with IEC 61125

### 3.2.2 ASTM D5837 (Modified) Standard Test Method for Furanic Compounds in Electrical Insulating Liquids by Gas Chromatography-Mass Spectrometry (GC/MS)

#### 3.2.2.1 Background

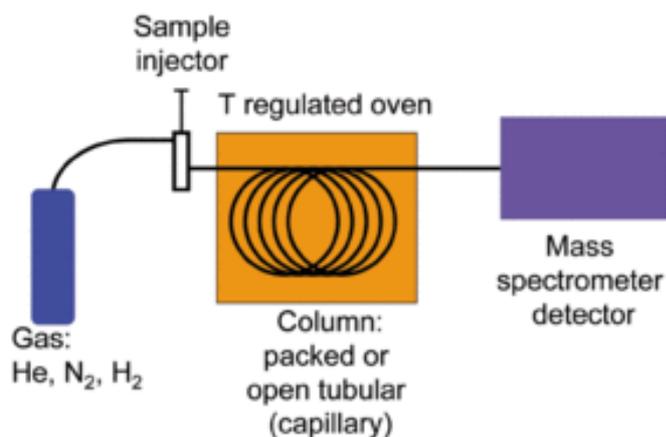


Figure 3-6: Gas Chromatography-Mass Spectrometer schematic

GC/MS has been used by Leblanc [18] in the identification and quantification of dissolved gases and furans concentration in transformer oil. It is a method that combines the features of gas-liquid chromatography and mass spectrometry to identify different substances within a test sample [48]. GC/MS was an invention developed by Roland Gohlke and Fred McLafferty in the 1950s. The machine was originally fragile and limited to laboratory settings but after continuous modification and development, it was soon discovered by many scientists that GC/MS had great potential in detecting organic compounds such as methanol, acetone, benzene, toluene, and 39carbon tetrachloride [48]. The machine composed of gas chromatography and mass spectrometer as shown in Figure 3-6 [48]. The difference in the chemical properties between different molecules in a mixture will separate the molecules as the sample travels the length of the column. As the molecules have different weight, each molecule take different amount of time to elute from the gas chromatograph. This characteristic allows the mass spectrometer to capture the ionized molecules at separated time [48]. The use of acetone in diluting furan derivatives in ASTM D5837[10], allows GC/MS to be used in detecting furan components like HPLC does.

HPLC is a form of column chromatography. It utilizes a column that holds chromatographic packing material (stationary phase), a pump that moves the mobile phase(s) through the column, and a detector that shows the retention times of the molecules. Components to be analyzed are first dissolved in a solvent, and then forced to flow through a chromatographic column under high pressure. The mixture that resolved into its components is detected by UV spectrometer. Sample result of furan measurement by HPLC is shown in Figure 3-7 [10]. The time at which the peak occurs in the corresponding chromatograms indicates the existence of the particular furan derivatives available in the oil sample.

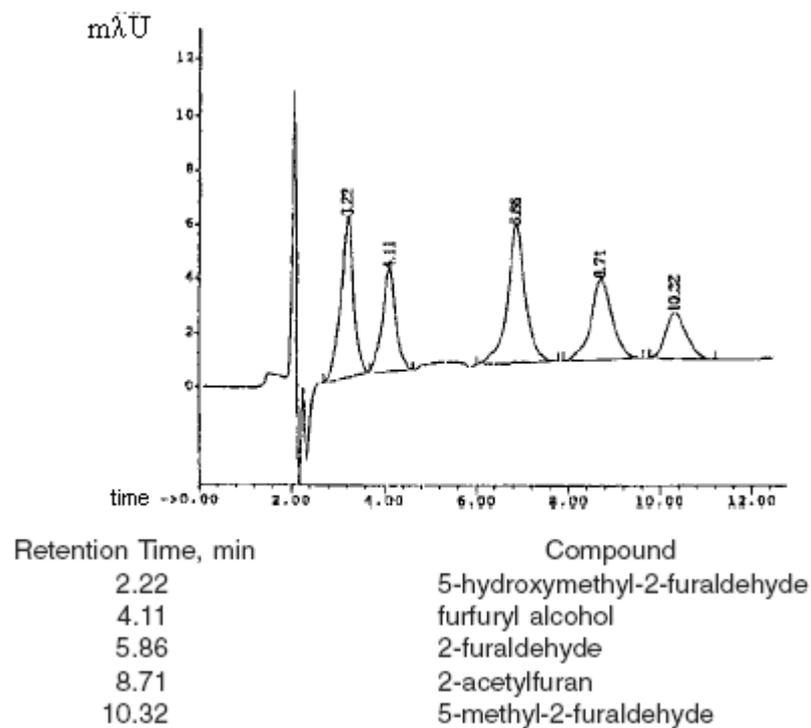


Figure 3-7 Example of chromatograms for furan derivatives identification by HPLC

### 3.2.2.2 Experiment

ASTM D5837 [10] is a standard used by industry engineers in determining furanic compounds concentration in electrical insulating oil using HPLC. However, the furan concentration measurement in this research project was done by using GC/MS. The liquid extraction procedure using extraction solvent (acetonitrile) in ASTM D5837 [10] is the same for the injection of specimen into GC/MS. The use of GC/MS instead of HPLC is considered the ASTM D5837 modified version.

For the furan testing of insulating oil in this research, ASTM D5837 (modified) was used for all necessary procedures used in the identification and quantification of furan contents in the oil by GC/MS. The experiments were conducted in the laboratory of industry. The tests were all closely supervised and monitored by the experts in those companies. It is noted that the accuracy of furan measurement from the GC/MS result is 0.01ppm. The normal cost of a furan test for one single sample was AUD\$150.

The individual furanic compounds that are identifiable and quantifiable by GC/MS are:

- 2-furaldehyde (2-FAL)
- 5-Hydroxy methyl-2-furfural (5-HMF)
- 5-Methyl-2- furfural (5-MEF)
- 2-Acetylfuran (2-ACF)
- Furfuryl alcohol (FOL)

Laboratory accelerated aged transformer oil and the in-service transformer oil samples collected from electrical utilities were tested for furan concentration by GC/MS. The liquid extraction procedure was done according to the ASTM D5837 procedure as below:

- 1) Measured 1 to 2 ml of acetone (extraction solvent) into 10ml of the test specimen in a test tube and capped securely.
- 2) Specimens were mixed using a vortex mixer for at least 3 minutes.
- 3) Then, the specimens were left in a closed cabinet (protected from sunlight) for at least 1 hour to allow the two phases to separate. The top phase was the extract, while the bottom phase consisted of the nonpolar portion of the test specimen

Instead of injecting the extracted sample into HPLC, the extract was run as it was at the mobile phase used as the start of the GC/MS run. Photograph of a GC/MS was shown in Figure 3-8. GC/MS then performed the furanic derivatives identification and quantification. The calibration of furanic compounds concentration standard in new transformer oil had already been done and tested by the experts in the company.



**Figure 3-8 GC/MS equipment used in this project**

### 3.2.3 ASTM E275 Standard Practice for Describing and Measuring Performance of Ultraviolet, Visible, and Near-Infrared Spectrometers

#### 3.2.3.1 Background

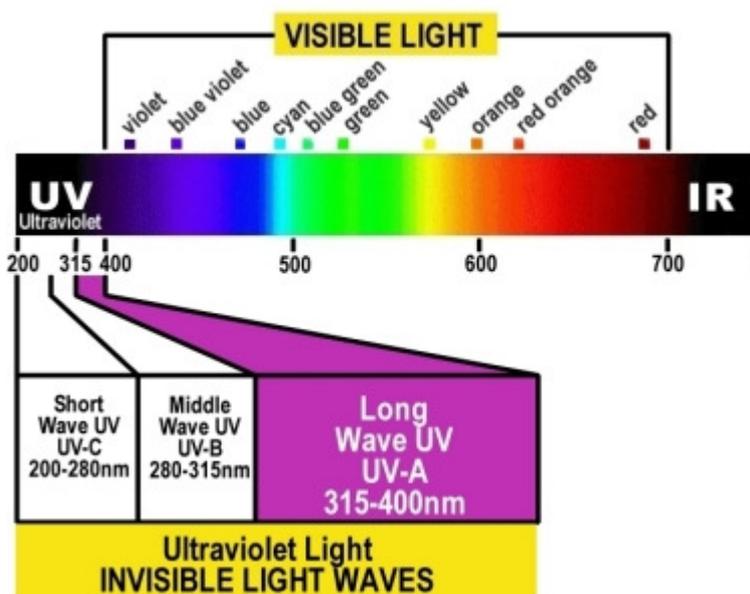


Figure 3-9: Light Spectrum in nanometers

Ultraviolet (UV) refers to the range of radiation invisible to human eyes, with the wavelength from 4nm to 400nm. Visible (Vis) are wavelengths between 400nm to 700nm that are classified as visible radiation. Figure 3-9 [49] shows an overview of the light spectrum in nanometers. UV light has been used in many applications, including UV/Vis spectroscopy for chemical structure analysis, mineral analyzing, and even to detect corona discharge effect on electrical apparatus [49]. UV-Vis spectroscopy is routinely used in the quantitative determination of solution of transition metal ions and highly conjugated organic compounds, like hydrocarbon mineral oil [49]. Organic compounds absorb light in the UV or visible regions of the electromagnetic spectrum. Furan derivatives are by-products from the degradation of cellulosic paper; therefore, they absorb UV or visible region light. In fact, HPLC in ASTM D5837 uses a UV detector to accurately identify and measure the concentration of each furan derivatives [10].

In the recent research done by Palmer [39] and Arshad [38], transformer oil of different age exhibit distinctive absorption band in the UV spectrum region. Their findings had revealed that different aging in transformer oil generates a different spectral response in the UV-Vis spectrum region. This research project is using normal absorption test to study the correlation between furan concentration in oil and its UV-Vis spectral response.

The UV-Vis spectroscopy analysis used to determine the furan concentration in transformer oil is governed by Beer-Lambert law [49]. The Beer-Lambert Law states that the absorbance of a solution is directly proportional to the solution's concentration [49]. The method is a quantitative way to determine concentrations of an absorbing species in a solution by this principal is [49]:

$$A = -\log_{10}\left(\frac{I}{I_0}\right) = \varepsilon \cdot c \cdot l \quad (3-1)$$

where  $A$  is the absorbance,  $I$  is the transmitted light intensity and  $I_0$  is the incident light intensity,  $\varepsilon$  is the absorbance coefficient of the absorbing species at a specific wavelength,  $c$  is the concentration of the absorbing species (grams per-litre), and  $l$  is the path length traversed by the light. Figure 3-10[50] is a figure description of Beer-Lambert Law in equation 3-1 [49].

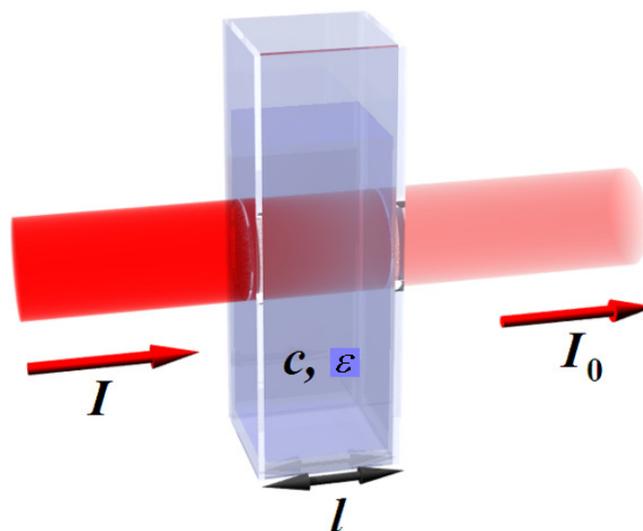


Figure 3-10: Schematic diagram of Beer-Lambert Law

It is important to note that for a sample of multiple species that absorb light at a given wavelength, the total absorbance at a given wavelength is the sum due to all the substances as illustrated below [49]:

$$A = \varepsilon_1 \cdot c_1 \cdot l + \varepsilon_2 \cdot c_2 \cdot l + \dots + \varepsilon_n \cdot c_n \cdot l \quad (3-2)$$

where  $A$  is total absorbance,  $\varepsilon_1, \varepsilon_2, \dots, \varepsilon_n$  is the absorbance coefficient of the absorbing species at that specific wavelength,  $c_1, c_2, \dots, c_n$  is the concentration of the absorbing species  $1, 2, \dots, n$  (grams per-litre), and  $l$  is the mean path.

Spectrophotometer is used in measuring UV-Vis spectroscopy. It measures the intensity of light passing through a sample ( $I$ ), and compared the intensity of its light to the intensity of incident light ( $I_0$ ). The ratio ( $I/I_0$ ) is called the transmittance, and expressed as a percentage as shown in the following [49]:

$$A = -\log\left(\frac{I}{I_0}\right) \quad (3-3)$$

The absorption test was affected by ambient light. Therefore equation (3-3) was modified to eliminate the intervention of ambient light in the absorption test. The absorption index used in this project was calculated based on the following equation:

$$A_\lambda = -\log_{10}\left(\frac{S_\lambda - D_\lambda}{R_\lambda - D_\lambda}\right) \quad (3-4)$$

where  $S_\lambda$  the test sample intensity at wavelength  $\lambda$ ,  $D_\lambda$  is the dark intensity with no test sample at wavelength  $\lambda$ , and  $R_\lambda$  is the reference intensity of test sample with zero contamination level at wavelength  $\lambda$ .

With reference to equation (3-4) and ASTM E275 [46], the developed UV-Vis spectroscopy analysis system design is shown in Figure 3-11. A UV light source (Deuterium Tungsten source) powered by a 240V AC supply, was connected to the test sample using fiber optic cable. The output light intensity from the test sample was captured by UV-Vis spectrophotometer through another fiber optic cable. The spectrophotometer then converted the analog input into digital data and fed this to the computer. The computer would require the necessary software program (Cross-Platform Spectroscopy Operating Software) to plot the spectral response curves from the test sample.

Comparing to HPLC, this system does not have a chromatographic packing material; thus, the test sample does not require the pre-treating process with acetone (solvent). The “raw” (untreated) insulating oil sample was just scanned with a UV light source powered by a 240V power supply. The response from the sample was captured by UV-Vis range spectrometer that also converted the data into a digital format and sent them to the computer. The absorption test results were spectral response of the entire contaminants (all furan derivatives) available in the transformer oil.

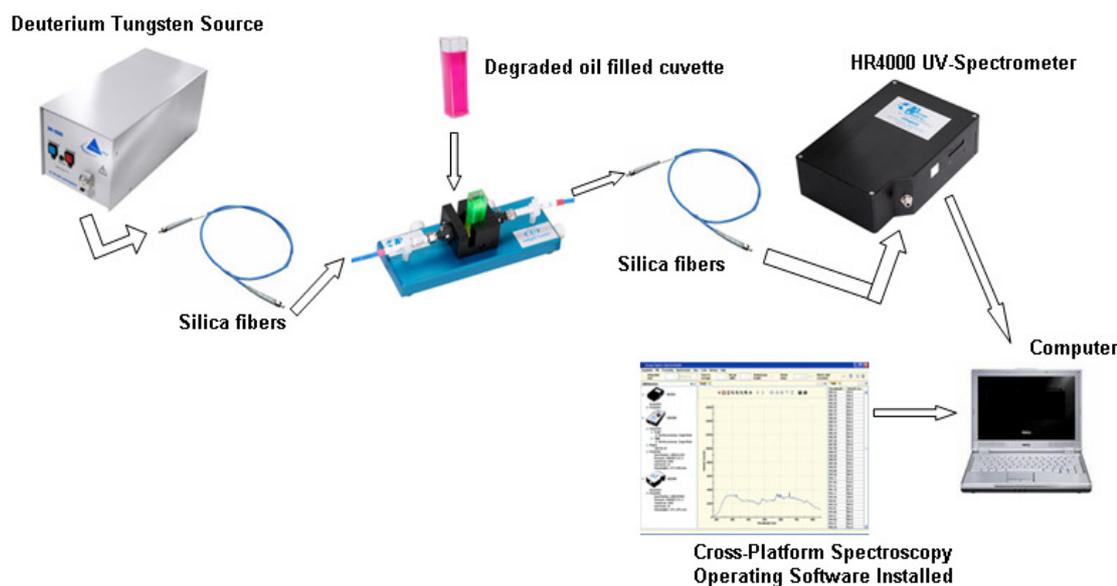


Figure 3-11 Schematic diagram of UV-Vis spectroscopic measurement system.

### 3.2.3.2 Experiment

ASTM E275 is the standard used as the reference for the practice of UV-Vis spectroscopy analysis in this research. It covers the practice and requirements of spectrophotometric performance especially for ASTM method [46]. This standard is useful as a guide in developing the experimental setup of UV spectral response measurement of oil samples that were already tested for furans concentration by GC/MS. Accurate spectrophotometry involves a large number of interrelated factors that determine the quality of the radiant energy passing through a sample and the sensitivity and linearity with which this radiant energy may be measured. According to the standard, the instrumental factors responsible for inaccuracies in spectrometry includes resolution, linearity, stray radiant energy, and cell constants [46]. Unfortunately, not all the factors that can affect the results are readily measured or

easily specified for the various types of spectrophotometric equipment [46]. The operator must describe the instrumentation and the performance required to duplicate the precision and accuracy when developing a spectrophotometric method. Any spectrophotometer may be described as a source of radiant energy, a dispersing optical element, and a detector together with a photometer for measuring relative radiant power. Even though most modern spectrophotometers have more accuracy than other analysts obtain, problem still lies in the selection and proper use of the instrumentation. Certain parameters that can control the result obtained are needed to be evaluated for proper instrumentation. These parameters are wavelength accuracy and precision, spectral slit width, photometry, and absorption-cell constants [46]. Improper use of instrumentation will lead to unsatisfactory measurement of any of these parameters mentioned above.

In obtaining spectrophotometric data, the proper instrumental operating condition is selected in order to realize satisfactory instrument performance. Although operating conditions for individual instruments are already obtained from the manufacturer's literature, it is still important to keep a record of documentation on the operating conditions selected. The documentation included the following factors:

- Ambient temperature
- Response time
- Mechanical repeatability
- Scanning parameters for recording instruments

These factors are important in the measurement of analytical wavelength and photometric data [46]. For example, changes in wavelength precision and accuracy can occur because of variation of ambient temperature of various parts of a monochromator.

The desired spectrometry analysis wavelength range in this research was between 200nm to 1100nm (UV-Vis). The general schematic of experimental setup plan is as illustrated in Figure 3-11. The lists of equipments used were:

- 1×Deuterium-Halogen Light source (240V AC powered)
- 2×50μm fiber optical cable
- 1×cuvette holder

- 1×HR4000 UV-NIR High Resolution Fiber Optic Spectrometer
- 100 CVD-UV disposable cuvettes

Deuterium-Halogen light source was used to generate the UV-Vis light. HR4000 was the spectrometer used for spectral response detection. Its resolution was as fine as 0.025nm. The data programmed memory chip in the spectrometer had already included the wavelength calibration coefficients and linearity coefficients. The components function in a sampling system is as below:

- 1) The user stores reference and dark measurements to correct for instrument response variables.
- 2) The light from the light source transmits through an optical fiber to the sample.
- 3) The light interacts with the sample.
- 4) Another optical fiber collects and transmits the result of the interaction to the spectrometer.
- 5) The spectrometer measures the amount of light and transforms the data collected by the spectrometer into digital information.
- 6) The spectrometer passes the sample information to SpectraSuite Spectroscopy Operating Software
- 7) The software compares the sample to the reference measurement and displays processed spectral information

The equipments were all calibrated by the manufacturer and brand new. No calibration is required as the equipments are already calibrated by manufacturer. In addition, the spectrometer does not have built-in slit, as the 50 $\mu$ m fiber optical cable's diameter has determined the size of the entrance aperture. During the running of the experiment, stray light was stored as dark spectrum and was terminated in the spectral response analysis. Therefore, the test result was not be affected by stray light even with the experiment done in a bright room. The CVD-UV disposable cuvettes used were made of plastic that work in the UV range is able to transmit light in the range of 220-900nm. The benefits of using disposable cuvettes are:

- Disposability prevents the risk of cross-contamination.
- No cleaning is required.

- High chemically resistance.
- Do not contribute to the measured UV absorbance of the sample.
- No difficulties related to dirty windows which absorb part of the radiant energy.

With these, the absorption-cells constant was ignored in this experiment. One of the uncontrollable factors that would affect the experiment is the ambient temperature. Therefore, the room temperature was taken every time before the experiment was started. Generally, the room temperature was between 20°C to 25°C when the experiments were conducted. The practical experiment connection for UV-Vis spectral response is shown in Figure 3-12.

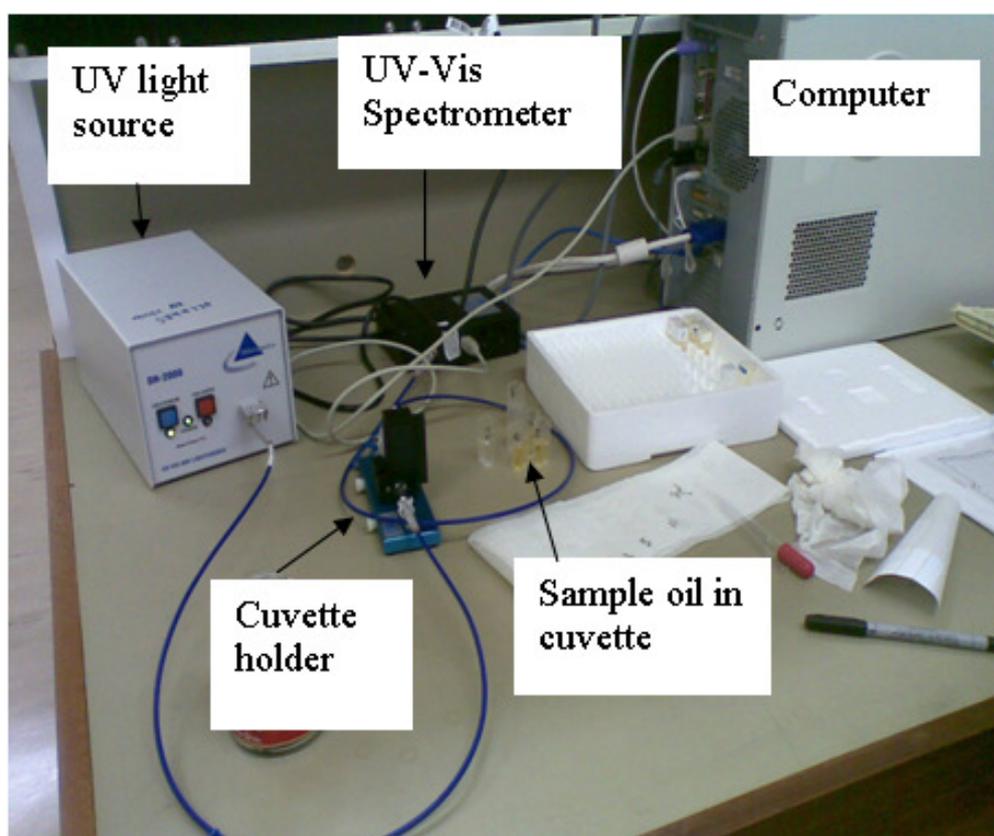


Figure 3-12 UV-Vis Spectroscopy furan measurement system

### 3.2.4 Dilution of High Furanic Oil Samples

As there were originally four different samples of furan concentration (3ppm, 5ppm, 10ppm, and 15ppm) collected from the electric supply company, oil sample at other furan concentration were prepared by using the dilution test. The dilution procedures and apparatus used were closely supervised and monitored by the laboratory staff in the chemical laboratory of Curtin University of Technology. Oil samples at other 2-FAL concentration were conveniently produced by diluting the collection of oil samples available. New oil samples at other furan content were prepared in a 10ml volumetric flask placed on a weighing scale with ambient temperature of 20°C. The desired 2-FAL concentration was calculated based on the equation 3-5 and 3-6 with transformer oil density of 0.889g/ml at 20°C:

$$A + B = 8.89 \quad (3-5)$$

where  $A$  is the weight of original furan content in grams and  $B$  is the weight of the new oil in grams. And

$$A = \frac{C}{D} \times 8.89 \quad (3-6)$$

where  $C$  is the desired 2-FAL concentration in ppm to be produced and  $D$  is the original 2-FAL concentration in ppm. Different eight concentration level samples were prepared as shown in Table 3-II.

**Table 3-II Diluted samples from different original furan concentration**

Original Furan Concentration (ppm)	Diluted sample (ppm)	Weight		New oil added (g)	Total Weight (g)
		Calculated (g)	Used (g)		
3ppm	0.5	1.481	1.501	7.400	8.901
	1.0	2.963	3.003	5.907	8.910
5ppm	2.0	3.556	3.582	5.323	8.905
10ppm	4.0	3.556	3.572	5.401	8.973
	7.0	6.223	6.249	2.69	8.939
15ppm	11.0	6.519	6.522	2.401	8.923
	12.0	7.112	7.120	1.776	8.896
	13.0	7.705	7.711	1.21	8.921

### **3.2.5 ASTM D 923 Standard Practice for Sampling Electrical Insulating Liquids**

Each oil sample was handled and stored in accordance to ASTM D923 Standard Practices for Sampling Electrical Insulating Liquids. It is a standard that covers the accurate practice in sampling electrical insulating liquids including oils, silicones, synthetic liquids and natural ester insulating liquids as well as insulating liquids in service or subsequent to service in cables, transformers, circuit breakers, and other electrical apparatus [45]. Gases, moisture, and furan derivatives contained in insulating oils are frequently used as an early indication for appropriate action to be taken on the equipment before it suffers greater damage [15]. Techniques in collecting and containing the samples contribute to the accuracy of measurement results.

This standard was strictly followed in handling and storage of the oil test sample used in the research to avoid the change in the properties that may lead to inaccurate measurement. Obviously, careless sampling procedure or contamination in sampling equipment, can lead to erroneous conclusions concerning the quality. In addition, it can result in loss of time and expenses in securing, transporting, and testing the sample. As the oil samples were collected from the electric supply company, the oil sample would have been collected according to the standard.

The standard was mainly used as guidance in storing the samples. All sample containers were stored in such a manner that the possibility of their being contaminated was eliminated as shown in Figure 3-13. The containers used were made of clear glass and sealed with aluminum cap. Containers were sealed as soon as the sample or test specimen was taken to prevent contamination by dirt or moisture. As soon as samples were taken, they were properly identified.

In addition, each container was carefully packaged to avoid spillage during the transportation. Since exposure to sunlight would promote photo-degradation, a layer of aluminum foil was wrapped around every container as shown in Figure 3-14. The samples were then kept in the cabinet at room temperature and protected from sunlight.



Figure 3-13 Sample collection of transformer oil with different furan content



Figure 3-14: Sample collections of oil stored according to ASTM D923

### 3.3 Result and Discussion

There were only a number of test specimens that had shown a high amount of furan concentration by the GC/MS. These samples of oil were from electrical utilities in South East Asian countries such as Indonesia, Singapore and Malaysia. Transformer oil in high humidity countries has higher furan concentration compared to those in Australian. This is attribute to the moisture contributes in higher furan generation, as according to the finding done by Hohlein [13].

There were a total of 10 insulating oil samples that were scanned with GC/MS. Six of the samples belonged to the laboratory aged oil that was explained in Section 3.2.1. The other four oil samples were collected from Indonesia, Singapore and Malaysia. These were the samples of oil with very high furan concentration that were provided by industry for this project.

The oil samples were then tested by using the UV-Vis spectrometry as mentioned in Section 3.2.3. Four samples of high furan content oil were diluted to produce test samples at differing furan concentration. The correlation between furan content and UV-Vis spectral response was investigated and demonstrated in this section. The experiment results indicated that UV-Vis spectrometry can, in the future, be an alternative in furan measurement.

#### 3.3.1 Furan Measurement by ASTM D 5837

The furan test result by GC/MS as according to ASTM D5837 (modified) principle is illustrated in Table 3-III. The results were expressed in parts per million (ppm). Table 3-III shows each furanic derivative (2-FAL, 2-FOL, 2-ACF, 5-HMF, and 5-MEF) concentration of all the insulating oil samples. Test sample from laboratory aged condition insulating oil were indicated by Laboratory aged. Insulating oil from in-serviced transformers are indicated by In-service 1, 2, 3, and 4. Diluted samples are indicated by Diluted 1 to 8.

**Table 3-III: Selected oil samples' test result by GC/MS**

Test Sample	2-FAL (ppm)	2-FOL (ppm)	2-ACF (ppm)	5-MEF (ppm)	5-HMF (ppm)
Laboratory aged	0.01	<0.01	<0.01	<0.01	<0.01
In-service 1	3.1	<0.01	0.01	0.01	<0.01
In-service 2	5.1	<0.01	0.02	0.01	<0.01
In-service 3	10.0	<0.01	0.03	0.03	<0.01
In-service 4	15.0	0.01	0.05	0.05	<0.01
Diluted 1	0.5	<0.01	<0.01	<0.01	<0.01
Diluted 2	1.0	<0.01	<0.01	<0.01	<0.01
Diluted 3	2.0	<0.01	0.01	0.01	<0.01
Diluted 4	4.0	<0.01	0.01	0.01	<0.01
Diluted 5	7.0	<0.01	0.02	0.02	<0.01
Diluted 6	11.0	0.01	0.02	0.02	<0.01
Diluted 7	12.0	0.01	0.03	0.03	<0.01
Diluted 8	13.0	0.01	0.04	0.04	<0.01

It was shown that laboratory aged oil by IEC61125 for 7 days is obviously insufficient to generate any significant amount of furan concentration. All the laboratory aged test samples had furan concentration that was lower than the detectable range of the GC/MS machine. However, four of the other oil samples (in-service) were showing relatively high furan concentration. Their test result had indicated that furan content is actually dominated by 2-furaldehyde (2-FAL). Almost 99% of the furan content was actually the (2-FAL). This is consistent with the on-site findings by many other researchers around the globe, where 2-FAL dominated the overall furan concentration in the insulating oil [19, 41, 42, 51, 52]. This has also proven that hydrolysis degradation is the major contributor for 2-FAL production [13]. Since these in-service oil samples were from South East Asia countries where the climate has high humidity all year round, higher furan content was expected. The diluted samples concentrations were also confirmed by GC/MS test result.

ASTM D5837 is reliable and accurate in identifying and measuring the concentration of furfural derivatives available in transformer oil. However, the problem with the standard is that the test is laborious and time consuming. The oil sample collected

from the site will need to be pre-treated with acetonitrile. The oil sample was mixed with a certain amount of acetonitrile (depending on the amount of test specimen), mixed using a vortex mixer for 3 min. The mixture was left in a cool temperature enclosed closet (protected from sunlight), for more than 2 hours to allow the two phases to separate. The top phase was the extract that consisted of diluted furan derivatives, while the bottom phase consisted of the nonpolar portion of the test specimen.

The extracted portion was the specimen that will be injected into a HPLC or GC/MS. It took up to 4 hours before the measurement result was available on the computer. After the last compound of interest elutes through the column, pure acetonitrile was injected into the machine to remove all oil contamination remaining in the analytical column. In addition, the use of HPLC or GC/MS requires daily basic calibration that may consist of development of calibration curve for each furanic compound, development of extraction efficiencies for each extracted furanic compound, and daily single-point calibration of equipment [10]. The use of ASTM D5837 requires a trained person to conduct the experiment. The cost of the GC/MS used in their laboratories was estimated as more than AUD \$50,000. Taking into consideration of the cost of chemical solvent, equipments apparatus, procurement and maintenance of HPLC or GC/MS machinery, this standard proves very expensive and time consuming for utilities to conduct. Therefore, most utilities send the testing to expert companies that provide the service. The consequence is that it increases the cost of maintenance and, due to a large number of test samples from other companies in the queue, the possibility of delay in getting the test result.

Overall, the disadvantages of using ASTM D5837 are summarized as below:

- a) Time consuming - 2 hours for pre-treating the oil, 4 hours for result to be obtained from GC/MS.
- b) Laborious - cleaning and regular calibration are required.
- c) Trained person required - increases the cost of furan testing.
- d) Expensive - GC/MS and all the other apparatus required.
- e) Immobilized - GC/MS is huge and off-site analysis may result in changing of sample originality during the transportation.

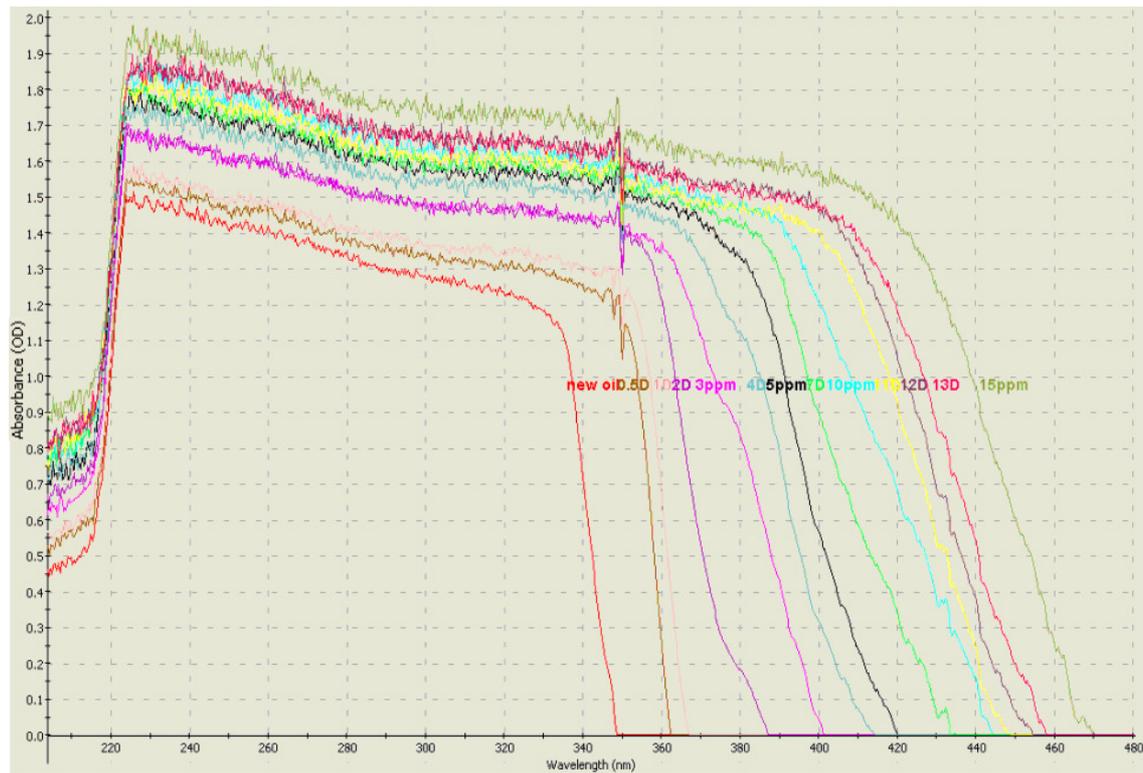
- f) Delay in obtaining the result – creates interruption of necessary action that should be taken to avoid substantial faults.

### 3.3.2 Furan Measurement by UV-Vis Spectroscopy at 20°C

All samples of oil that were tested with GC/MS were again tested by UV-Vis spectrometry. Handling and transporting of these oil samples were done according to the ASTM D923 to preserve the originality of the oil. A total of 13 oil samples at different furan concentration were available for UV-Vis spectrometry analysis.

Using the experimental setup as demonstrated in Figure 3-12, UV-Vis spectrometry analysis was commenced. The ambient temperature of 20°C was recorded as this is part of the external factor that may affect the experimental results. Approximately 2ml of each oil sample was injected into a clean disposable cuvette. Sample cuvette was then placed in a cuvette holder to be scanned for UV-Vis spectral response analysis.

The UV-Vis spectral response of these oil samples showed a very satisfactory result as shown in Figure 3-15. The spectral response of the oil sample changed in correlation with the furan concentration available. New oil with 0ppm 2-FAL, indicated by the red color, had the shortest and lowest spectral response compare to the others. The spectral response of the highest 2-FAL concentration, indicated by dark green, had the widest absorption wavelength bandwidth and highest absorption peaks. In between them, the spectral response in the UV-Vis range increased in correlation with the furanic compounds concentration. Similarly, absorption peaks increased with higher furan content available in transformer oil.



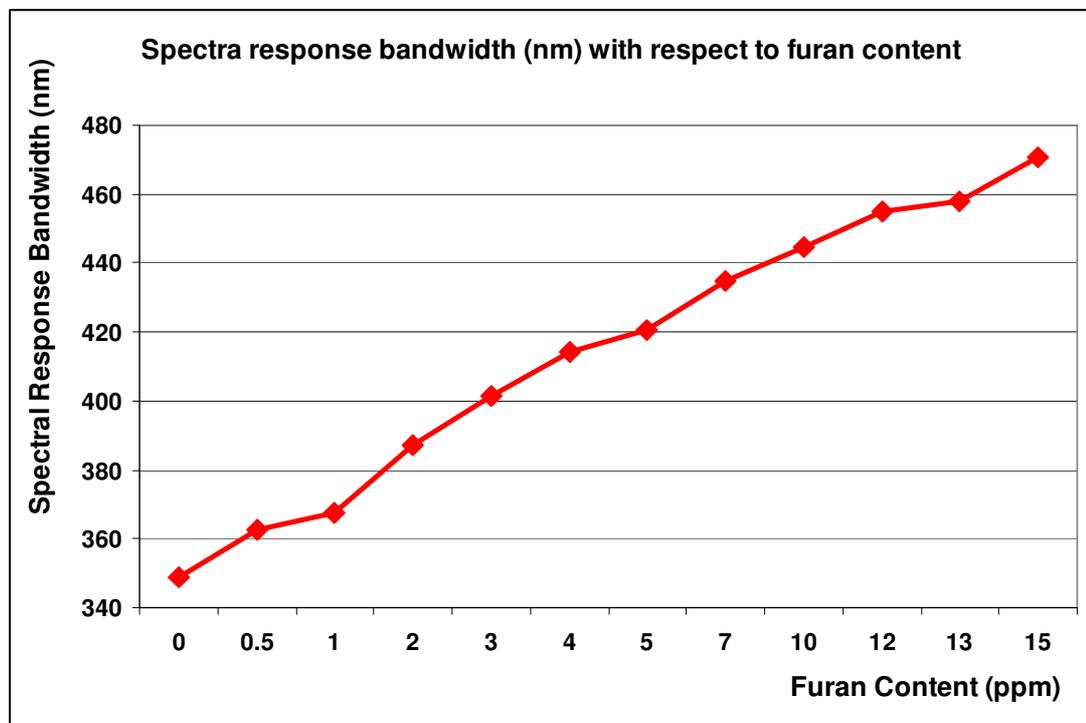
**Figure 3-15 UV-Vis absorption spectral response at various furans content level**

It was observed that spectral response in the UV-Vis range was increasing along with the furan content available in the transformer oil. There were two parameters identified to have significantly changed with respect to furans concentration. They are the spectral response bandwidth length (zero crossing points) and the maximum absorption peak height. For furanic concentration in between 0 ppm to 15 ppm, the maximum absorption peaks ranged from 1.5000 to 2.0000. In addition, absorption peak are concentrated in the range of 220nm to 230nm.

The details of bandwidth wavelength and its maximum absorption peak for each furans concentration was summarized in Table 3-IV. The values of bandwidth and absorption peak were determined based on the average of 50 numbers of UV-Vis spectrometry scans on the sample oil. Absorption test has proven that UV-Vis spectral response from transformer oil is strongly correlated with its furans concentration. The relationship of bandwidth and furan content is plotted in Figure 3-16. The data was taken from the measurement result in Table 3-IV. As shown in Figure 3-16, there is almost a linear relation between bandwidth and furan concentration.

**Table 3-IV Bandwidth length and absorption peak at different furans content level**

Furan contents (ppm)	Curve color	Spectra response bandwidth (nm)	Maximum absorption peak ( $A_\lambda$ )
0	Red	348.76	1.5000
0.5	Light brown	362.55	1.5045
1	Pink	367.32	1.5710
2	Purple	387.14	1.6625
3	Light purple	401.55	1.6700
4	Grey	414.33	1.7410
5	Black	420.39	1.7805
7	Green	434.76	1.8030
10	Blue	444.44	1.8360
11	Yellow	449.50	1.8510
12	Maroon	454.80	1.8670
13	Dark red	458.07	1.8715
15	Dark Green	470.51	1.9465



**Figure 3-16 Spectral response bandwidth with respect to furan content**

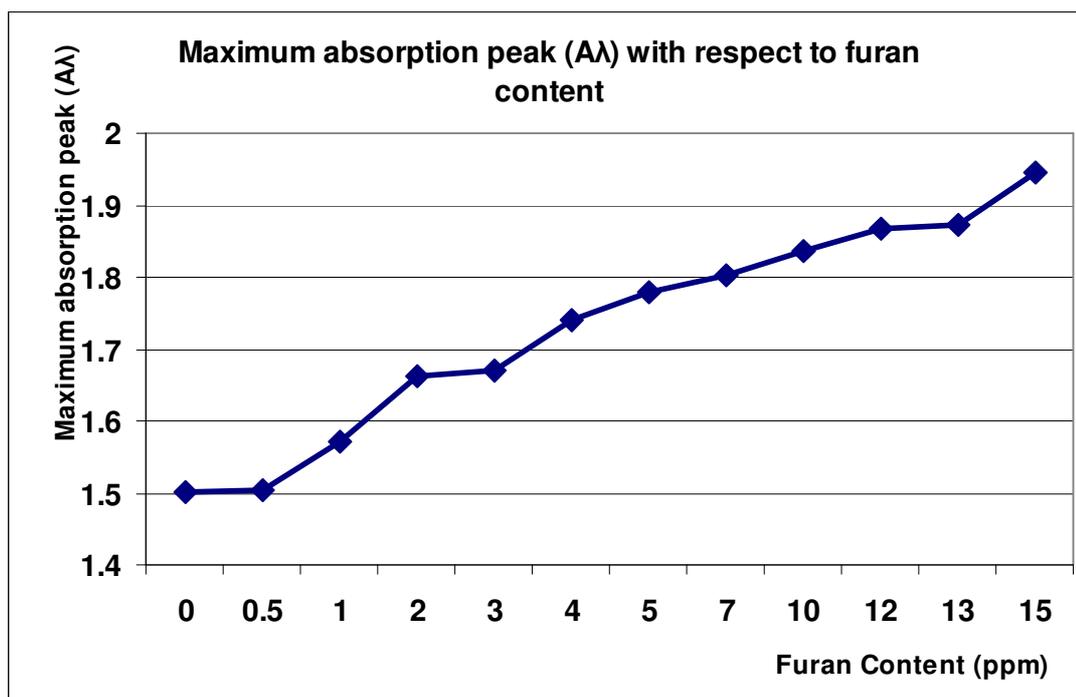
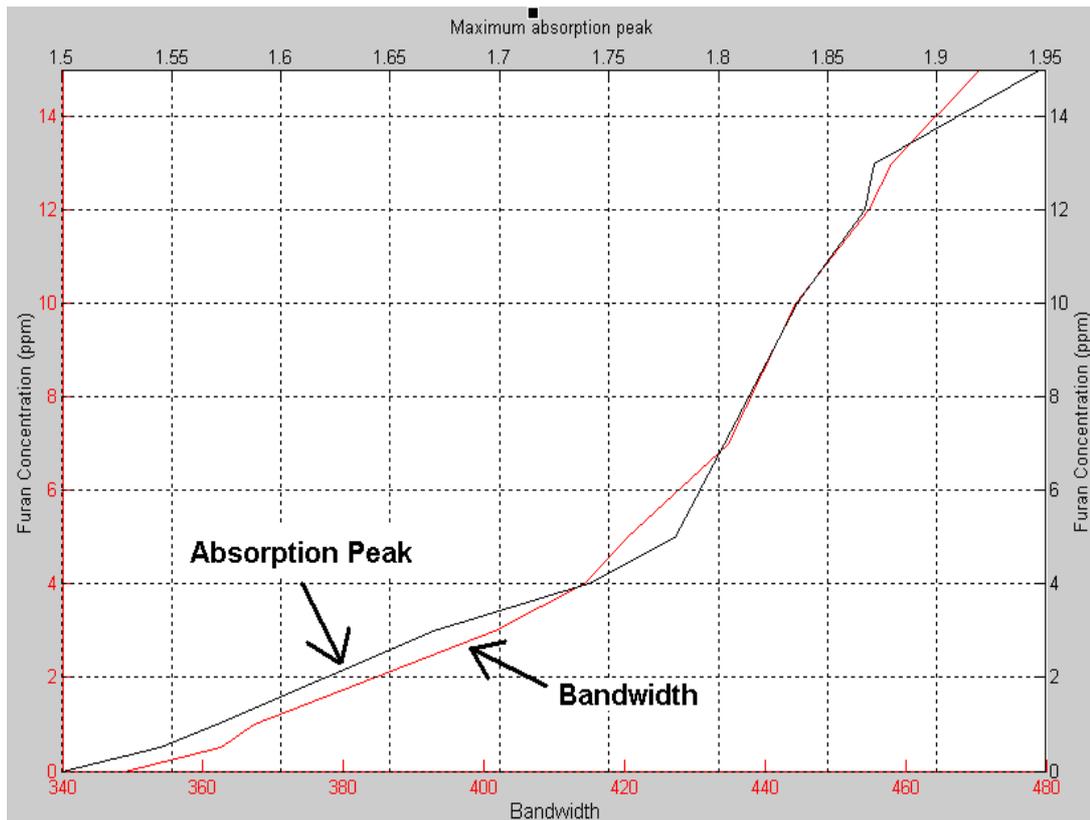


Figure 3-17 Maximum absorption peak (Aλ) with respect to furan content

There was also a significant change in the absorption peak values with respect to its 2-FAL concentration in transformer oil. The absorption peaks and furan content relationship is plotted in Figure 3-17.

High correlation was obtained between these two parameters and furan content. It can be concluded that absorption bandwidth and peaks values obtained from UV-Vis spectrometry analysis are useful parameters in predicting the corresponding furan content level.

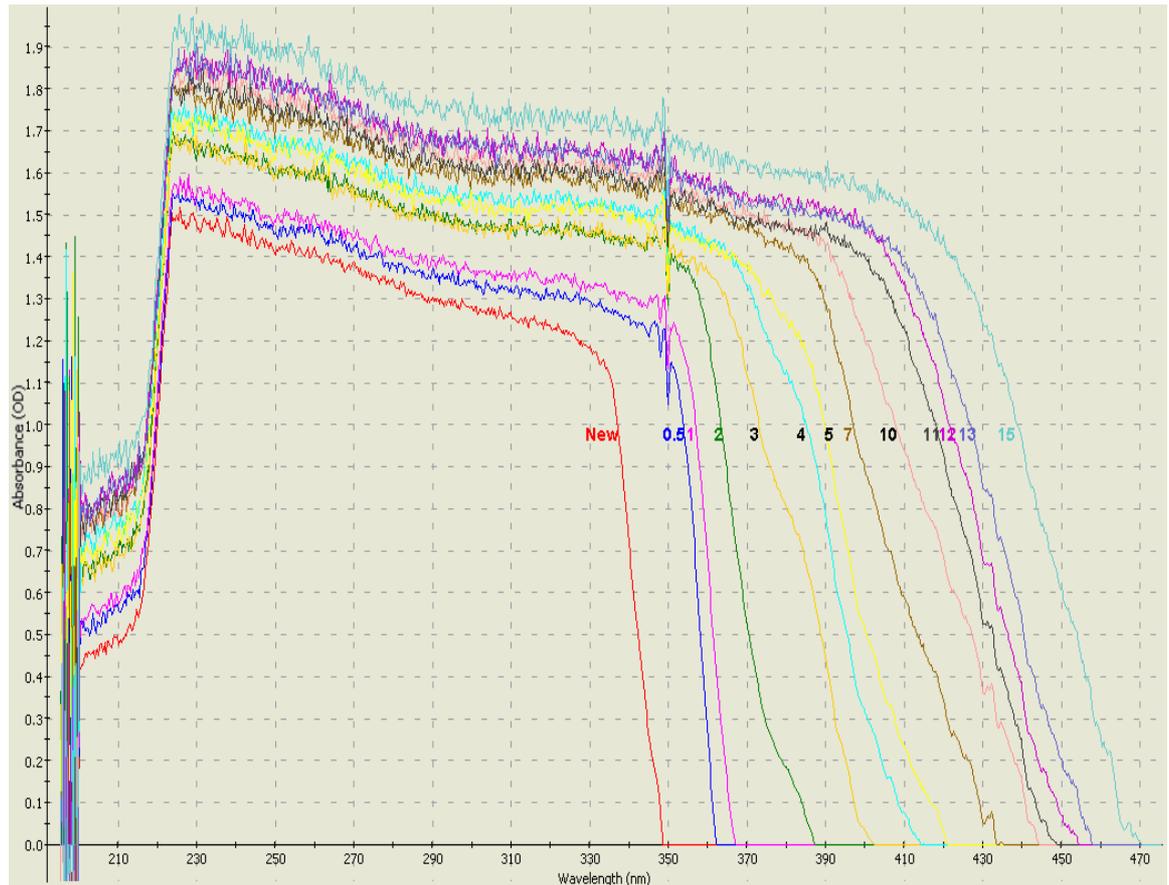
A very interesting characteristic is found when the absorption bandwidth and peaks were plotted on to the same Y-axis as shown in Figure 3-18. The graph displays almost parallel curves of bandwidth values and absorption peak values with respect to furan concentration. Therefore, these two parameters are reliable input parameters for the Fuzzy Logic modeling of furans content estimation that will be investigated in the next chapter



**Figure 3-18 Linearity between bandwidth and absorption peak in relation to 2-FAL concentration level**

### 3.3.3 Furan Measurement by UV-Vis Spectral Response at 25°C

Ambient temperature is one of the uncontrollable external factors that may affect the spectral response result as mentioned in ASTM E275 [46]. Changes in spectral wavelength precision can also occur because of variation in ambient temperature [45, 46]. Therefore, all oil samples were rescanned for UV-Vis spectral response analysis when the room temperature was at 25°C. The corresponding spectral response found is shown in Figure 3-19. The waveform shapes found are almost identical to the spectral response at 20°C. The absorption bandwidth and maximum peak values for each curve is recorded in Table 3-V. There are slight variations in the bandwidth and absorption peaks value as compared to Table 3-IV.



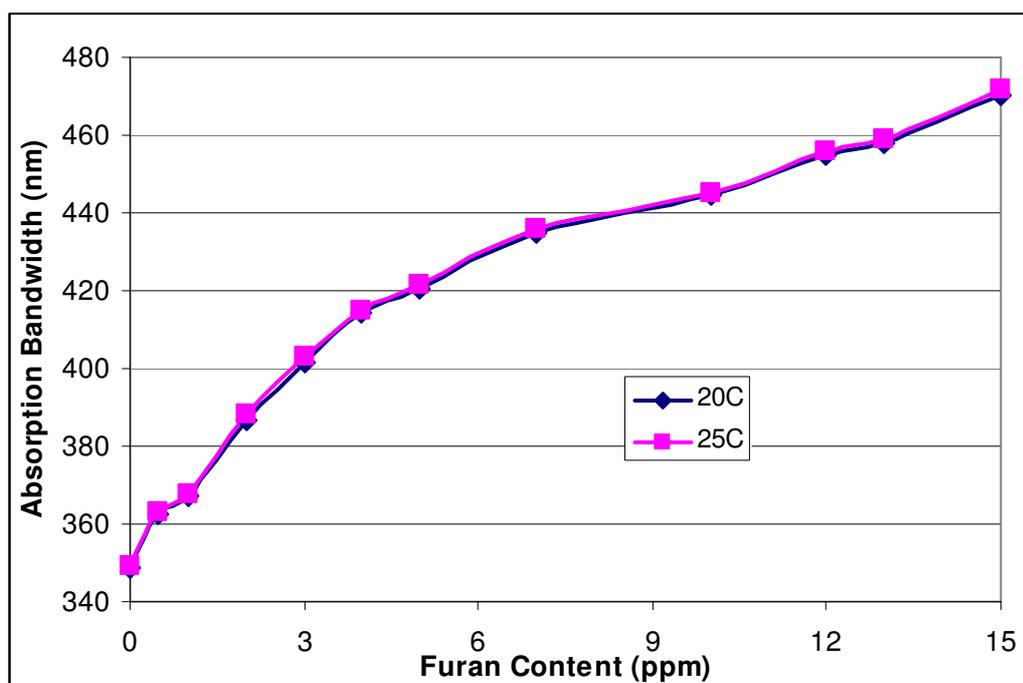
**Figure 3-19: UV-Vis spectral response at ambient temperature of 25°C**

Figures 3-20 and 3-21 show the variation in spectra response parameter due to different ambient temperatures. For the same 2-FAL concentration, increment of temperature from 20°C to 25°C have expanded the bandwidth by an average value of 0.96nm as shown in Figure 3-20. The increment of ambient temperature by 5°C does not produce any significant changes in absorption bandwidth for the same level of furan concentration in transformer oil.

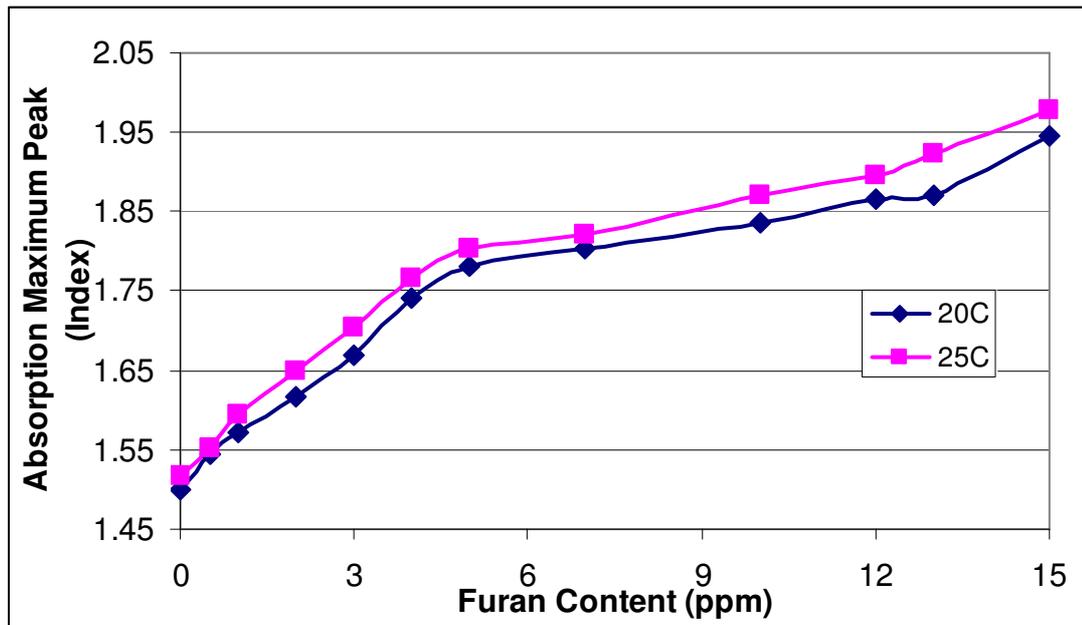
Figure 3-21 illustrates the range of variation of absorption peaks variation for ambient temperatures 20°C and 25°C. The increment of ambient temperature from 20°C to 25°C, increases maximum peaks value of 0.027 index. Even though the variation is insignificant, this differences is taken into account in the fuzzy logic model.

**Table 3-V Slight variation in absorption bandwidth and maximum absorption**

Furan contents (ppm)	Ambient temperature of 20°C		Ambient temperature of 25°C	
	Spectra response bandwidth (nm)	Maximum absorption peak ( $A_\lambda$ )	Spectra response bandwidth (nm)	Maximum absorption peak ( $A_\lambda$ )
0	348.76	1.5000	349.29	1.516
0.5	362.55	1.5445	363.08	1.551
1	367.32	1.5710	367.85	1.595
2	386.63	1.6160	387.95	1.650
3	401.55	1.6700	403.26	1.705
4	414.33	1.7410	415.12	1.767
5	420.39	1.7805	421.44	1.804
7	434.76	1.8030	435.90	1.821
10	444.44	1.8360	445.36	1.870
12	454.80	1.8670	455.84	1.896
13	458.07	1.8715	458.99	1.923
15	470.51	1.9465	471.55	1.977



**Figure 3-20 Spectral bandwidth variation range for ambient temperature between 20°C and 25°C at different furans concentration**



**Figure 3-21** Maximum absorption peak variation range between ambient temperature of 20°C and 25°C at different furans concentration

As discussed, UV-Vis spectral response is strongly correlated with furan concentration in oil, UV-Vis spectroscopy analysis for furan content measurement is achievable. Compared to the conventional method of ASTM D5837, UV-Vis spectrometry is much more convenient and economical. The benefits of using UV-Vis spectrometry compared to ASTM D5837 are summarized as below:

- a) Convenient - no need to pre-treat the sample oil with any solvent.
- b) Simple – does not require a trained person to conduct the test.
- c) Economical – UV-Vis spectroscopy equipment and all other apparatus are less than AUD\$12000.
- d) Mobility – UV-Vis spectrometry equipments is small and has potential for development of hand-carried set to allow tests conducted on-site.
- e) Sensitivity – UV-Vis spectral response is sensitive to furan content level in oil as will be shown in the next chapter.

### **3.4 Summary**

This chapter explains the details of experimental work done in the research and the standards that are followed to ensure the quality of the research outcome. The significance of the experiment is to prove that furan content in transformer oil is correlated to UV-Vis spectrometry even without pre-treating the oil. The spectral response absorption bandwidth expands and maximum peak increases in response to furan content increment. These two parameters are identified as useful indicators for predicting furan content in transformer oil.

## 4 FUZZY LOGIC MODELING

### 4.1 Introduction

This chapter explains in details the software simulation model. The purpose of the software model is to predict the furan content available in transformer oil sample by using the parameters of its UV-Vis spectral analysis. By using MATLAB platform, a simulation model to predict furan content based on Fuzzy Logic approach is developed. The result from the simulation model has more than 95% accuracy in comparison to the furan measurement result by conventional method (ASTM D5837 [10]). A comparison is made between the conventional method and the developed UV-Vis spectrometry with Fuzzy Logic approach in furan content measurement. It is found that UV-Vis spectrometry with Fuzzy Logic approach is more beneficial than the conventional method in a number of ways. The general conclusion is that an alternative in measuring furan contents in transformer oil has been developed in this research.

### 4.2 Fuzzy Logic for Furan Estimation

The advantage of fuzzy logic concept is its capability to get a definite conclusion easily based upon vague, imprecise, or noisy input parameters. The parameters used as inputs for the fuzzy logic model of this research will be the UV-Vis spectral response absorption bandwidth wavelength and its maximum absorption peaks. These two parameters will be used in estimating the furan concentration available in the oil. Even though this method by Fuzzy Logic approach is less precise than ASTM D5837, their use is closer to human intuition because it is built on rules from human experience and not based on formulas. Plus it exploits the tolerance of imprecision and uncertainty to achieve tractable and lower solution cost. Fuzzy Logic provides an alternative solution in characterizing spectral response to furan concentration.

The detail of Fuzzy Logic concept is available in Appendix A. As this research is on the application of Fuzzy Logic, this section is illustrating the development of Fuzzy Logic model to estimate furan content in transformer oil. Fuzzy logic is “soft-

computing” methodology that has variables whose values are generally words that are based on fuzzy if-then rule. In this sense, fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the concepts of fuzzy logic rely on age-old skills of human reasoning [53].

Therefore, with a sufficient amount of data, fuzzy logic can be a convenient way to map an input space to an output space. Mapping input to output is the starting point of all fuzzy logic modeling. The graphical presentation of an input-output map for the model that presents the furan concentration based on UV-Vis spectral response bandwidth and maximum absorption peak, is depicted in Figure 4-1. Figure 4-1 shows that by inserting UV-Vis range absorption test bandwidth and maximum peaks into the fuzzy logic model (“black box”), the output from the model is the furan content value.

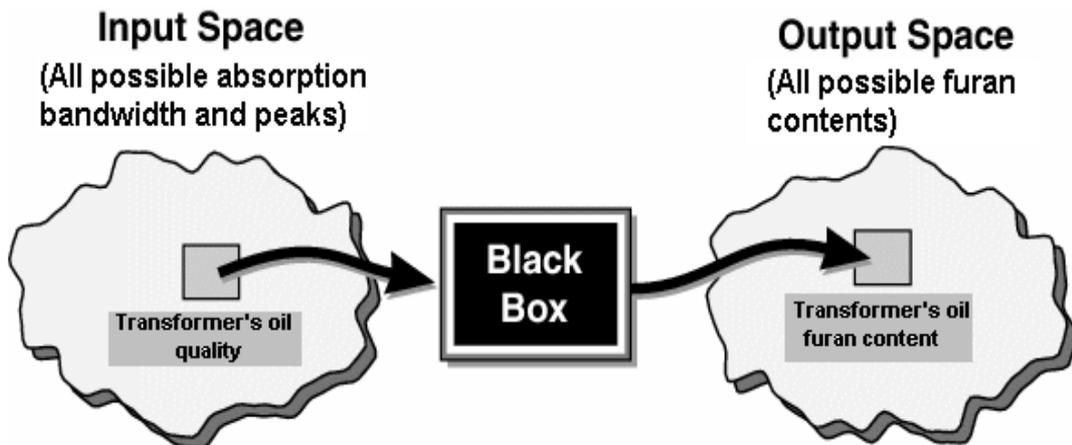


Figure 4-1 Input-output map for furan content estimation

### 4.3 Model Design Approach

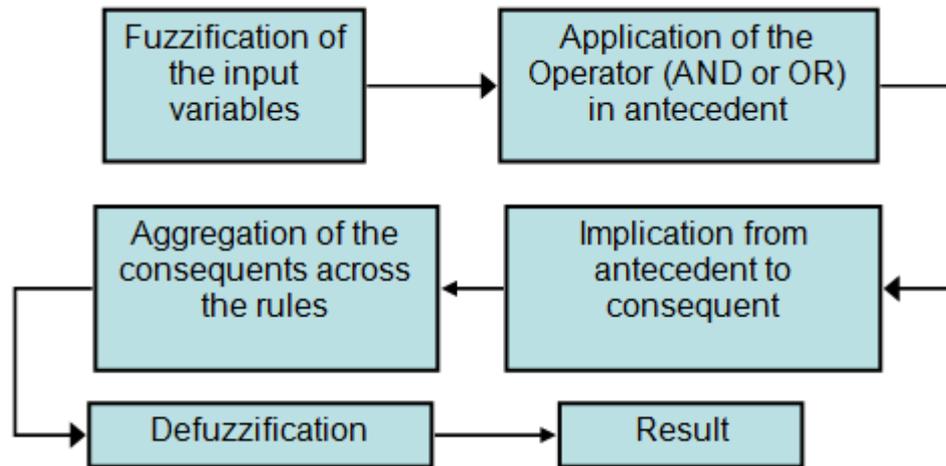


Figure 4-2 Fuzzy Inference flow chart for model development

Figure 4-2 shows the flow chart that is summarizing the procedures for the software development of furan content estimation based on the Fuzzy Logic approach. The model is built by using the graphical user interface tools provided in MATLAB. This is the design detail procedures of the “Black Box” in Figure 4-1. Inputs variable for the model are the values of absorption test bandwidth wavelength and maximum absorption peak collected from UV-Vis spectrometry test. The software model developed applicable for furan testing in room temperature between 20°C to 25°C. Details for each of the steps in Figure 4-2 is

#### 4.3.1 Fuzzification of Input Variables

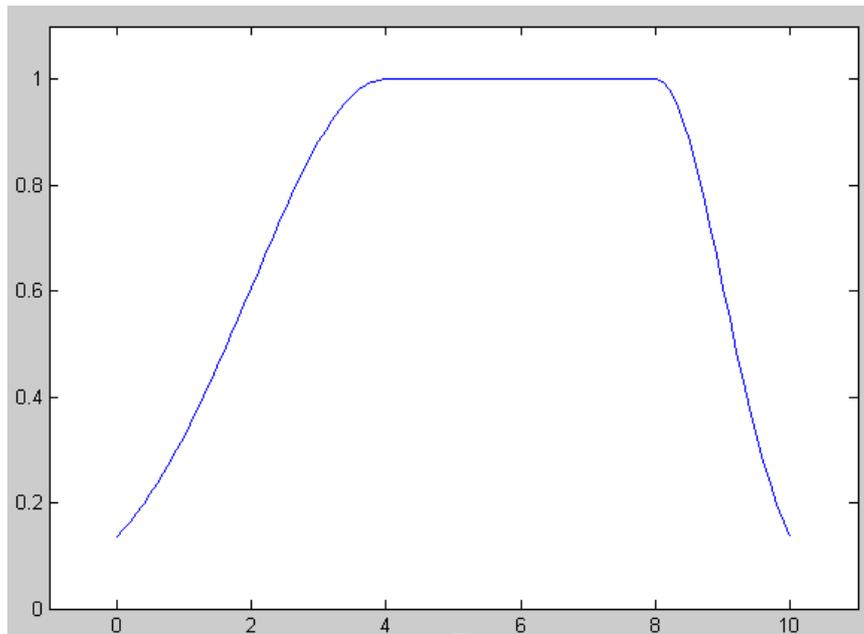
The start of the process is the fuzzification of input variables (absorption bandwidth and peak). Gaussian combination membership function is used to describe the input parameters (absorption bandwidth and peak). Each input is fuzzified into 10 sets of Gaussian combination membership function. The single Gaussian function is governed by:

$$f(x; \sigma, c) = e^{-\frac{(x-c)^2}{2\sigma^2}} \quad (4-1)$$

where  $c$  is the mean and  $\sigma$  is the variance.

Gaussian combination membership function is the combination of these two Gaussian functions in equation 4-1. Therefore, the 10 sets of fuzzified Gaussian

combination membership function are a function set developed by the combination of  $\sigma$  and  $c$  parameters, where first function,  $\chi=1$ , specified by  $\sigma_1$  and  $c_1$  will determine the shape of the left-most curve; the second function,  $\chi=2$ , specified by  $\sigma_2$  and  $c_2$  will determine the shape of the right-most curve. Sample of a Gaussian combination membership curve with  $\sigma_1=2$ ,  $c_1=4$  and  $\sigma_2=1$ ,  $c_2=8$  is shown in Figure 4-3.

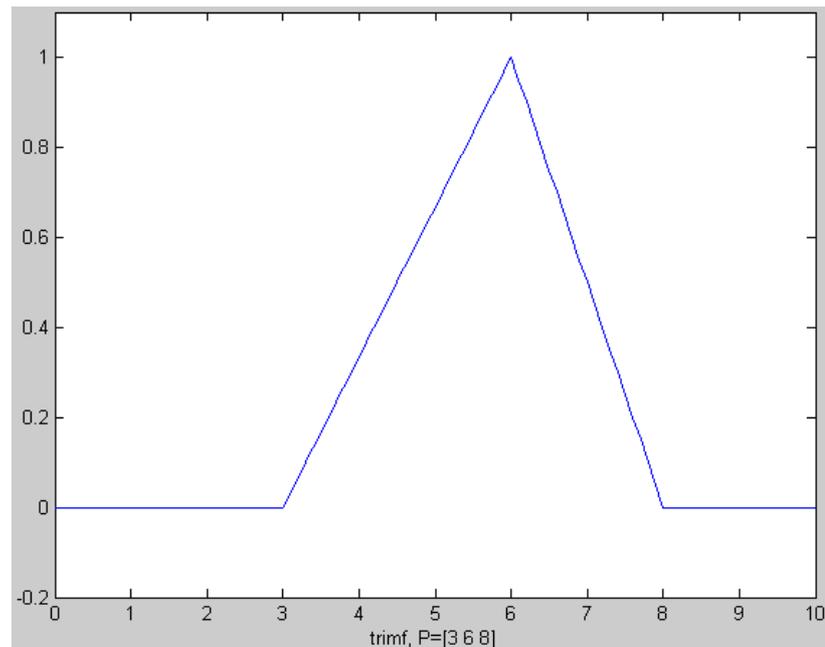


**Figure 4-3: Gaussian combination membership function curve**

Output parameter (furan content) is also need to be fuzzified in order to be simulated by the Fuzzy Logic model. Triangular-shaped membership function is used to describe the output function. Each output parameter (furan concentration) is fuzzified into a triangular function based on the following:

$$f(\chi; a, b, c) = \begin{cases} 0, & \chi \leq a \\ \frac{\chi - a}{b - a}, & a \leq \chi \leq b \\ \frac{c - \chi}{c - b}, & b \leq \chi \leq c \\ 0, & c \leq \chi \end{cases} \quad (4-2)$$

where a function  $\chi$  is depend on  $a$  and  $c$  that locate at the “feet” of the triangle, and  $b$  locates the peak. A sample figure of triangular membership function waveform with  $\chi$  range from 0 to 10,  $a=3$ ,  $b=6$ , and  $c=8$ , is shown in Figure 4-4.



**Figure 4-4: Triangular membership function curve**

Schematic diagram of how fuzzification works for input parameter is shown in Figure 4-5. For example, the spectral response bandwidth, which is always the crisp numerical value limited to the universe of discourse of the input variable, in this case the interval between 348 and 475 nm. The output is a fuzzy degree of membership in the qualifying linguistic set, which is always in the interval between 0 and 1. The fuzzy logic model is built based on 100 rules, and each rule depends on resolving the inputs into a number of different fuzzy linguistic sets. Before the rules can be evaluated, the inputs must be fuzzified according to each of these linguistic sets. For example, to what extent is the furan content at a particular concentration? Figure 4-5 shows how high the furan concentration of a particular oil test sample is qualified (via its membership function) as the linguistic variable of bandwidth. In this case, the furan content is 2 ppm which given the graphical definition of bandwidth, corresponds to  $\mu = 0.13$  for the bandwidth membership function.

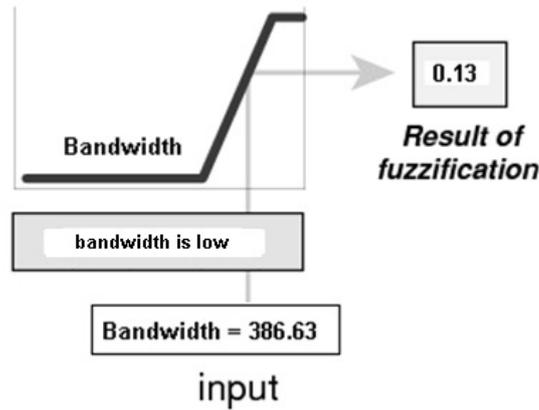


Figure 4-5: Graphical illustration of fuzzification for input bandwidth parameter

### 4.3.2 Apply Fuzzy Operator

After the inputs are fuzzified, the degree to which each part of the antecedent is satisfied for which rule is known. As there are more than one antecedent of a given rule, the fuzzy operator is applied to obtain one number that represents the result of the antecedent for that rule. The number will then be applied to the output function.

The AND operation is used on the input numbers, using the two built-in AND methods, which are *min* (minimum) and *prod* (product). The Figure 4-6 shows the AND operator, evaluating the antecedent on the rules for the furan content calculation. The two different pieces of the antecedent (bandwidth is low and absorption peaks is low) yielded the fuzzy membership values of 0.13 and 0.13 respectively. The Fuzzy AND operator will make sure that both values are in the same set, and the fuzzy operation for the selected rule is complete. The operation AND method would still result in 0.13.

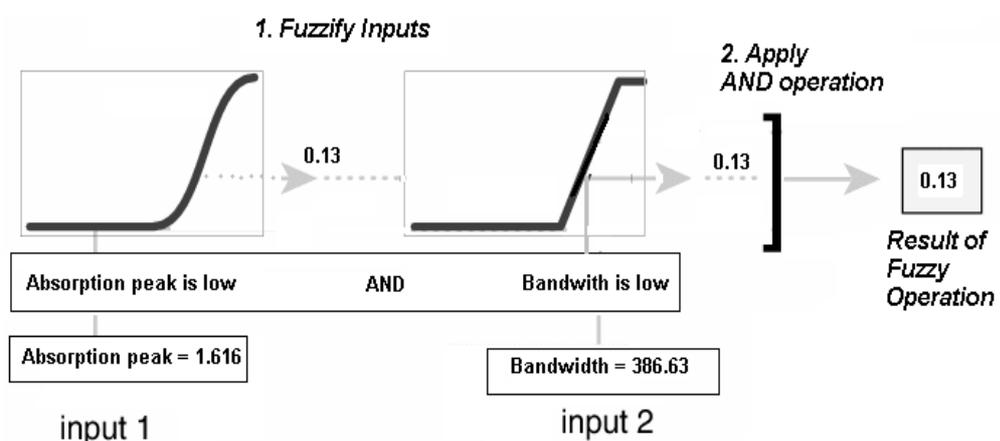


Figure 4-6: Graphical presentation for application of the Operator AND

### 4.3.3 Apply Implication Method

Prior to applying the implication method, the rule's weight is has been determined. In MATLAB platform, every rule has a weight (a number between 0 and 1), which is applied to the number given by the antecedent. The implication method can only be correctly implemented after proper weighting has been assigned to each rule. A consequent is a fuzzy set represented by a membership function, which weights appropriately the linguistic characteristics that are attributed to it. The consequent is reshaped using a function associated with the antecedent. The input for the application process is a single number given by the antecedent, and the output is a fuzzy set. Implication is then implemented for each rule. As for this case, the method AND operator is used: min (minimum), which truncates the output fuzzy set, and prod (product), which scales the output fuzzy set. Graphical presentation of applying implication method is as shown in Figure 4-7.

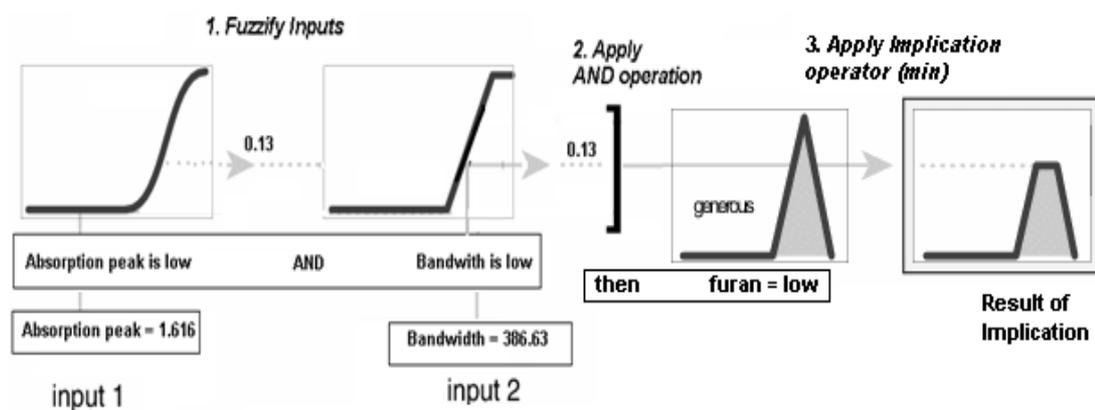


Figure 4-7: Schematic diagram of applying implication method

### 4.3.4 Aggregate All Outputs

As the decisions are based on the testing of all the rules in a Fuzzy Inference System, the rules must be combined in some manner in order to make a decision. Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. Aggregation only occurs once for each output variable, just prior to the fifth and final step, defuzzification. The input of the aggregation process is the list of truncated output functions returned by the implication process for each rule. The output of the aggregation process is one fuzzy set for each output variable. Graphical demonstration is shown in Figure 4-8. As long

as the aggregation method is commutative (which it always should be), then the order in which the rules are executed is unimportant. In other words, the order of rules does not affect the process of aggregating the result. MATLAB supports three built-in methods:

- Max (maximum)
- Probor (probabilistic OR)
- Sum (simply the sum of each rule's output set)

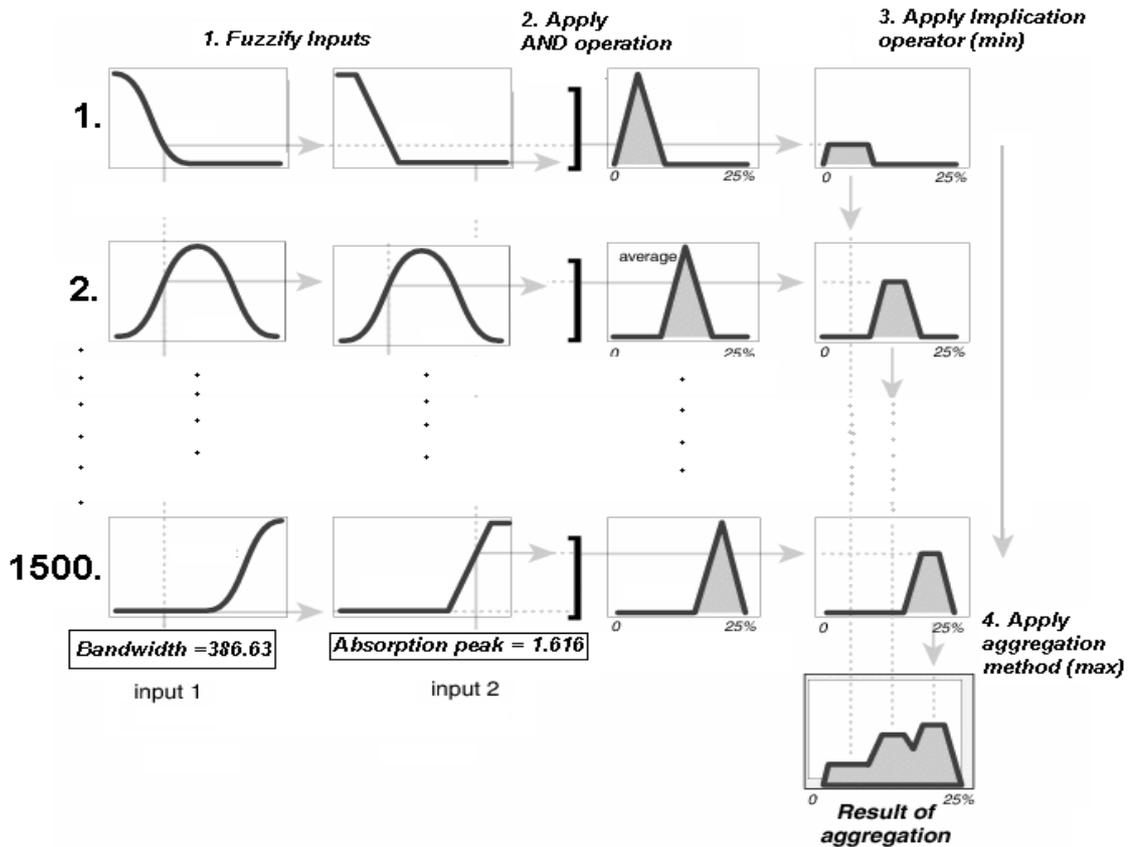


Figure 4-8: Schematic diagram of aggregation of all outputs

### 4.3.5 Defuzzification

The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. With the fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variables is generally a single number. However, the aggregation of a fuzzy set encompasses a range of output values, and must be defuzzified in order to resolve a single output value from the set. The defuzzification method used in this fuzzy logic model is the centric calculation, which returns the center of area under the curve. Graphical presentation of the defuzzification is as show in Figure 4-9.

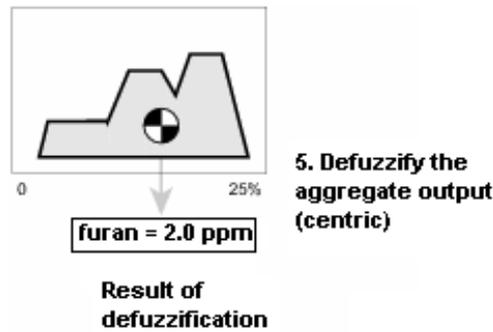


Figure 4-9: Schematic diagram of defuzzification

### 4.4 System Modeling in MATLAB

Using the Fuzzy Inference System flow chart in the previous section, a fuzzy logic simulation model was developed using MATLAB. The fuzzy logic simulation model was able to predict the furan concentration based on the input parameters of UV-Vis spectral response bandwidth and absorption maximum peak value. In reference to equation 4-1, the corresponding curve for the input variables of bandwidth wavelength is depicted in Figure 4-10. The  $\sigma$  and  $c$  parameters for each set of Gaussian combination function that describe the input UV-Vis absorption bandwidth is in Appendix B.

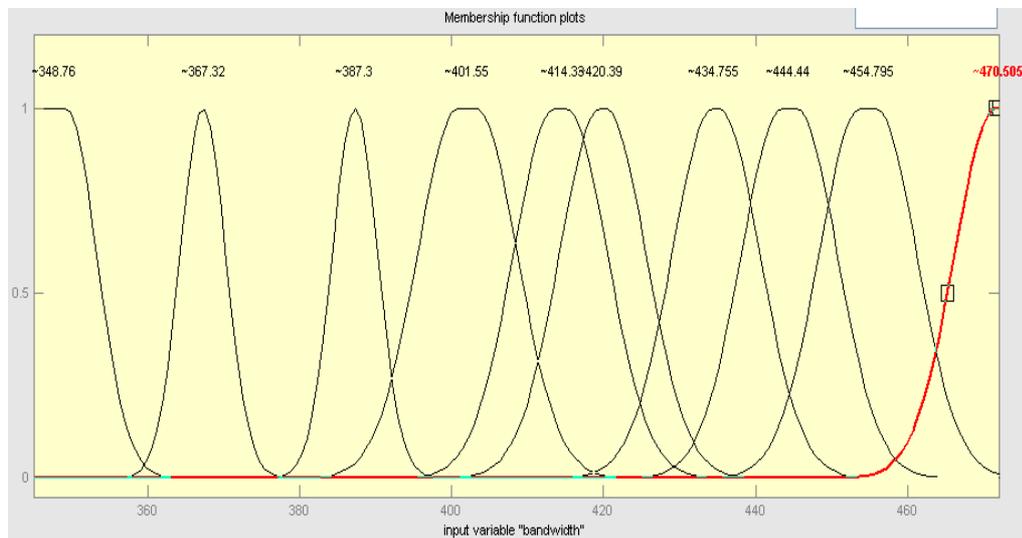
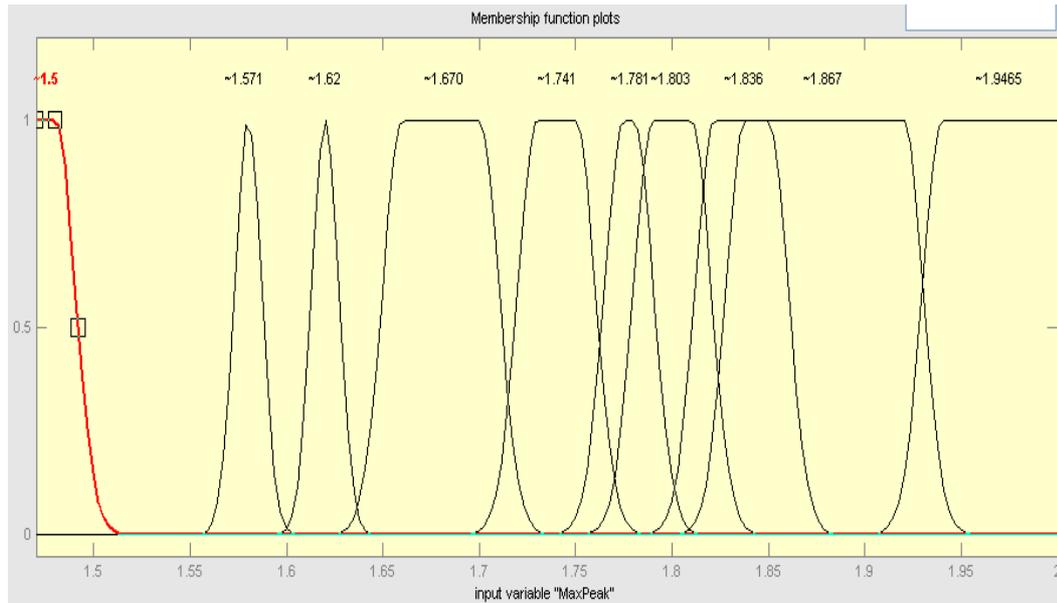


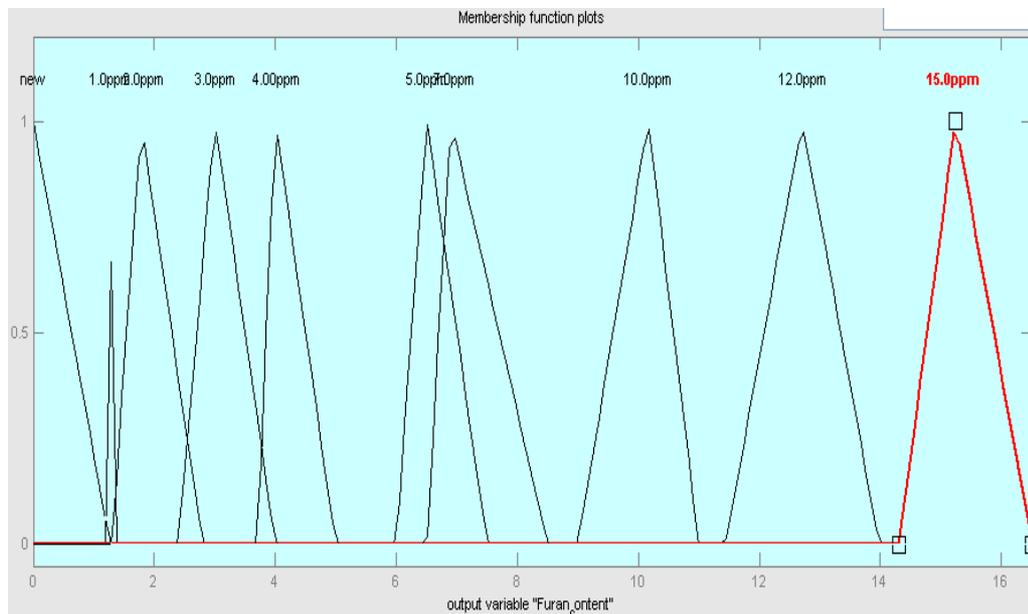
Figure 4-10 Gaussian combination membership function curves for UV-Vis absorption bandwidth

Using the same equation (4-1), the curve for the input variables of maximum absorption peak is depicted in Figure 4-11. Their  $\sigma$  and  $c$  parameters for each set of Gaussian combination function are in Appendix B.



**Figure 4-11 Gaussian membership function for maximum absorption peak**

In reference to equation (4-2), the corresponding 10 sets of fuzzified triangular-shaped membership curves are plotted in Figure 4-12. Their parameters of  $a$ ,  $b$ , and  $c$ , for the triangular membership function is in Appendix B.



**Figure 4-12 Triangular membership function for furan concentration output**

For the application of operator AND in the antecedent mentioned in Section 4.3.3, the Fuzzy Logic model is governed by IF-Then rules. As there are 10 sets of membership function available, a total of 100 set of rules were added into the system

to allow the system to aggregate across all possible outcomes. The 100 set of rules based on IF-THEN rules are listed in Appendix C.

The completed furans estimation model has an interface shown in Figure 4-13. The model developed was able to estimate the furan concentration with more than 95% accuracy compare to GC/MS measurement result. Variables *BW* and *Absorption* represent the spectral response bandwidth and peak absorbance respectively, as an input data to the fuzzy model and *t* is the step time for the fuzzy model simulation. Figure 4-14 illustrates the interface which shows the estimated furans content level based on the inputs of UV-Vis absorption test bandwidth and maximum peak. The mapping from the inputs of bandwidth and absorption peak to the furan concentration output is illustrated in a three-dimensional graph shown in Figure 4-15.

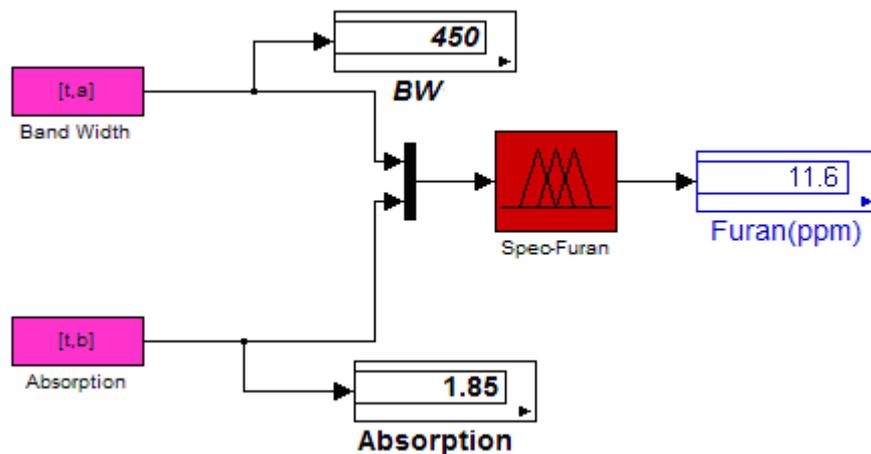


Figure 4-13 Furan estimation fuzzy logic model

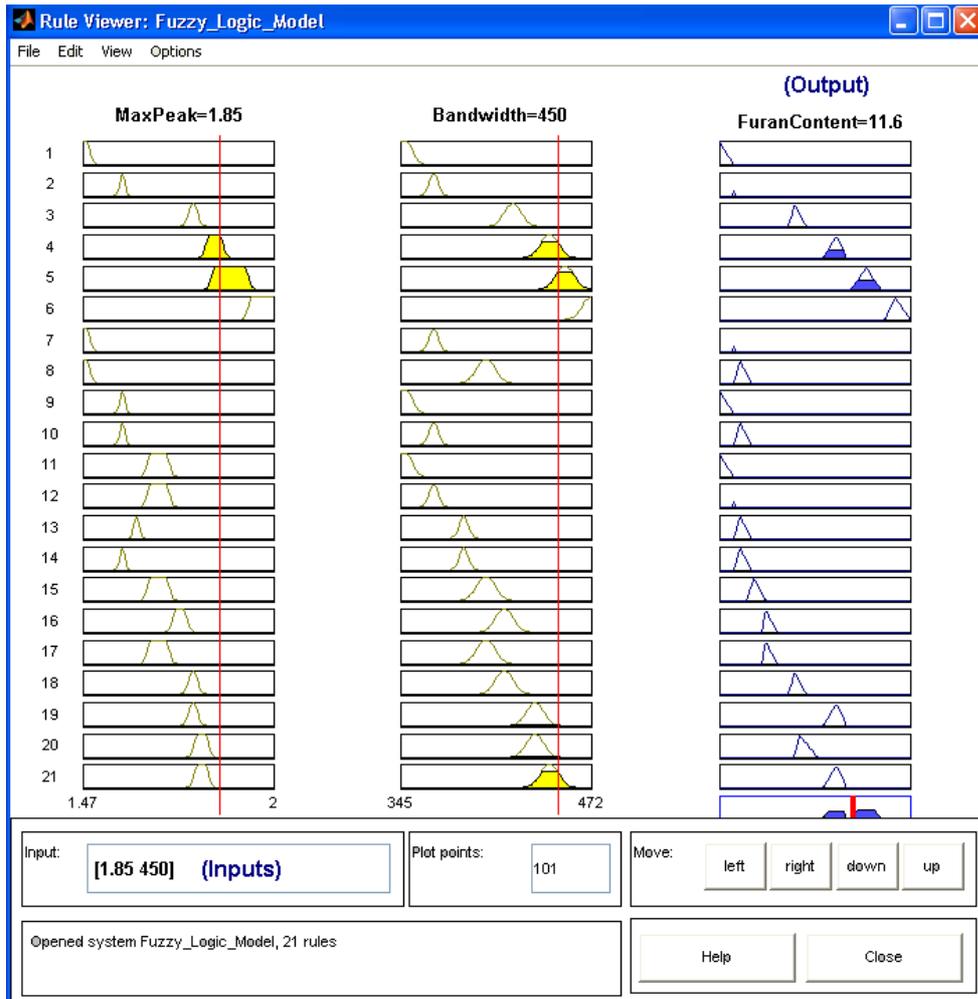


Figure 4-14 Furans concentration level estimation display based on the bandwidth and absorption peak inputs

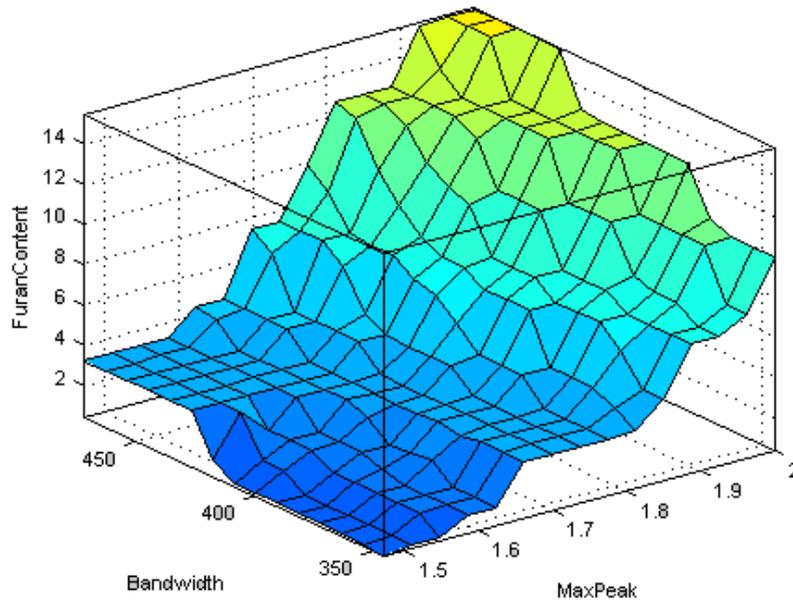


Figure 4-15 Three-dimensional mapping from bandwidth and absorption peak to furan concentration

#### 4.5 Verification of Simulation Model

The simulation model developed was able to estimate furan content with more than 95% accuracy compared to the measurement result from ASTM D5837. The maximum range of the simulation model able to accurately estimate the furan content in transformer oil is 15ppm. The maximum range of the output parameter is sufficient to indicate the deterioration of the solid insulation inside the transformer. As mentioned in the survey done by Sans [42], for a furan concentration higher than 5ppm, the possibility of transformer failure is very high. Summary of the percentage of error for the simulation model compared to GC/MS measurement result is shown in Table 4-IV.

**Table 4-I Comparison between simulation and field measurement result**

Inputs		Outputs		Percentage of error (%)
Spectra response bandwidth (nm)	Maximum absorption peak ( $A_\lambda$ )	ASTM D 5837 Furan contents (ppm)	Simulation Model Estimation Furan contents (ppm)	
348.76	1.5000	0	0.03	3.00
362.55	1.5045	0.5	0.51	1.57
367.32	1.5710	1	1.05	4.76
386.63	1.6160	2	1.98	-1.00
401.55	1.6700	3	3.13	4.15
414.33	1.7410	4	4.20	4.76
420.39	1.7805	5	5.20	3.85
434.76	1.8030	7	6.98	-1.45
444.44	1.8360	10	10.22	2.20
454.80	1.8670	12	12.20	1.64
458.07	1.8715	13	13.31	2.38
470.51	1.9465	15	15.32	1.96

## 4.6 Comparison between ASTM D5837 and UV-Vis Spectroscopy with Fuzzy Logic

ASTM D5837 is widely adopted for accurate identification and quantification of furan derivatives available in transformer oil. However, testing with HPLC or GC/MS requires trained personnel, tedious pre-treating of test samples and definitely is a very expensive method. Therefore, most electric supply companies utilize another private company that provides the necessary specialized services. This will incur more financial expense into the asset management of the company. In addition, it may have to wait a long period of time to receive the result of the test. There maybe also be a possible risk of contamination to the originality of the insulating oil samples during the transportation from the utility to the servicing company.

By proposing UV-Vis spectroscopy, electrical utilities have the alternative to estimate the overall furans condition in the oil before it is found necessary to be sent for a standard test. It is because the method is relatively simple that it does not require trained staff to conduct the experiment. It saves costs due to the reason that equipment used for UV-Vis spectrometry is at least four times cheaper than HPLC or GC/MS. Besides which, pre-treatment of the oil sample is not required. The sample of result can be obtained instantly - unlike ASTM D5837 [10], where it would take at least four hours to know the furan concentration. Most importantly, the accuracy of the developed method has more than 95% accuracy of the ASTM D5837. In addition, the other benefit of UV-Vis spectrometry analysis is its mobility that allows engineers to conduct the furan test on site. This will eliminate the risk of losing oil properties in the transportation of oil samples from site to laboratory. The comparison between ASTM D5837 and UV-Vis spectrometry with Fuzzy Logic analysis is summarized in Table 4-II. With these advantages, there is potential to implement this method in the industries and to be commercialized.

**Table 4-II Comparison between ASTM D 5837 and UV-Vis Spectroscopy with Fuzzy Logic**

Criteria	ASTM D 5837	UV-Vis Spectroscopy with fuzzy logic
Test method	Requires trained person to prepare the sample and handle the experiment. Oil samples needed to be pre-treated with acetone.	Does not require trained person to conduct the experiment. Oil samples don't have to be pre-treated with any chemical reagent.
Time taken to conduct the test	>4hrs	Instantly
Mobility	GC/MS or HPLC is relatively huge and furan testing can only be conducted in laboratory	Equipments can be hand-carried and conduct furan testing conducted on-site.
Risks	Risk of losing originality of sample during transportation from site to laboratory	none
Price of Equipment	>AUD \$50,000	< AUD \$12,000
Accuracy	Able to identify and quantify the concentration for every single furan derivatives	Shows the response as a whole. However, 99% of furan concentration is dominance by 2-furfural.

## 4.7 Summary

Simulation model based on Fuzzy Logic theory incorporated with UV-Vis spectral response analysis is developed for better furan content in oil testing. The model is designed on MATLAB platform. Using UV-Vis absorption test bandwidth and maximum peak as input parameters, a Fuzzy Logic based simulation model can estimate furan content in oil with accuracy of more than 95% in comparison to the conventional technique. This developed method allows furan content in oil analysis to be more convenient, simpler and economical.

## 5 CONCLUSION AND FUTURE RESEARCH

### 5.1 Conclusion

This research has demonstrated the use of UV-Vis spectroscopy and Fuzzy Logic approach in estimating furfural concentration in unprocessed transformer oil. It is shown that UV-Vis spectral response is strongly correlated to the furan concentration in transformer oil. The UV-Vis spectral response bandwidth and maximum absorption peak increased in accordance to the furan concentration. These two parameters provided significant indication of furan concentration in oil. The effect of ambient temperature to the UV-Vis spectral response analysis is also investigated. The experimental result from this research has provided the opportunity to develop a novel technique for a better and easier method of measuring furans in transformer oil analysis. By using MATLAB platform, a simulation model based on Fuzzy Logic theory is developed to estimate furans concentration in transformer oil. Using UV-Vis range absorption test response's bandwidth and maximum peak values as input parameters, the simulation model is able to predict furan concentration at more than 95% accuracy in comparison with the conventional technique. This novel method also provides other benefits such as convenience, simplicity, mobility and economy in comparison to ASTM D5837. The commercial values of this research have attracted attention from researchers and power industry engineers during presentation in conferences.

### 5.2 Further Recommendations

The research has developed an alternative for furan measurement in transformer oil. However, the UV-Vis spectral response from the transformer oil will change with a variation in ambient temperature [46]. The UV-Vis spectral response is analyzed under ambient temperatures of 20°C and 25°C. The differences found are insignificant to create any substantial variation between the two temperatures. Due to unavailability of necessary equipment, analyses at other ambient temperatures were not investigated. It is essential to analyze the spectral response at other ambient temperatures for the practicability and accuracy of the developed technique. It is

therefore recommended that UV-Vis spectral response at other temperature levels should be investigated.

In addition, for the purpose of commercializing the method, it will have to be verified with more field studies. This research has proven the relationship between the furan concentration and UV-Vis spectrometry. It also provided an accurate simulation model to predict the furan content; simplified the process and saved more costs compared to the conventional method (ASTM D 5837). However, as some of the laboratory prepared test samples of various furans content level may possibly not be identical to the condition of site-collected operating transformer oil, it is necessary to test the model with field studies prior to introducing it into the industries.

### **5.3 Key Contribution**

Power transformers are critical pieces of equipment in the power industry. Condition monitoring such as solid insulation strength assessment in electrical equipments, has been the standard practice of electrical utilities for continuous and safe distribution of power. In this thesis, a novel method is developed for furan measurement in oil filled power transformers based on UV-Vis spectrometry and Fuzzy Logic Theory. The developed technique is able to complement all the obstacles in the current standard practice of ASTM D5837[10] used in the insulating oil furans analysis. Summarized in Table 5-I, novel UV-Vis spectroscopy with Fuzzy Logic analysis is an alternative for furan measurement in transformer oil.

By using novel UV-Vis spectroscopy with Fuzzy Logic analysis, furans in transformer oil can be inspected conveniently, easily, accurately and economically. The technique reduces the complexity in furans testing and the electrical utility does not need to employ other companies in diagnosing the solid insulation condition of their transformers. In addition, the technique can also improve the operation and safety of power transmission and distribution systems by allowing necessary actions to be taken early and avoiding catastrophic consequences related to transformer insulation failure.

**Table 5-I: Key Contribution of novel UV-Vis spectroscopy and Fuzzy Logic analysis**

<b>UV-Vis Spectroscopy with Fuzzy Logic Analysis</b>	<b>ASTM D5837</b>
<p>Simple</p> <ul style="list-style-type: none"> <li>- Sample oil does not require pre-treating process</li> </ul>	<p>Laborious</p> <ul style="list-style-type: none"> <li>- Oil samples need pre-treating procedure by acetonitrile</li> </ul>
<p>Rapid</p> <ul style="list-style-type: none"> <li>- Seconds to generate results</li> </ul>	<p>Time-consuming</p> <ul style="list-style-type: none"> <li>- Takes more than 4 hours to produce results</li> </ul>
<p>Convenient</p> <ul style="list-style-type: none"> <li>- Equipments are small and mobile</li> <li>- Allows furan test to be conducted on-site</li> </ul>	<p>Inconvenient</p> <ul style="list-style-type: none"> <li>- Equipments are large and immobilized</li> <li>- Risk of loss of sample oil's properties during the transportation from site to laboratory</li> </ul>
<p>Economical</p> <ul style="list-style-type: none"> <li>- Equipments costs less than AUD\$12000</li> <li>- Does not required trained person in conducting the test</li> </ul>	<p>Expensive</p> <ul style="list-style-type: none"> <li>- Equipments costs more than AUD\$50000</li> <li>- Trained person is required in conducting the experiment</li> </ul>
<p>Accurate</p> <ul style="list-style-type: none"> <li>- More than 95% accuracy</li> <li>- Measures the total response but 99% of furan derivatives is dominated by 2-FAL</li> </ul>	<p>Very Accurate</p> <ul style="list-style-type: none"> <li>- Able to identify and quantify each furan derivatives</li> </ul>

---

**REFERENCE**

- [1] S. J. Chapman, "Why Transformer are Important to Modern Life," in *Electric Machinery Fundamentals*, Fourth ed Australia: McGraw Hill, 2005, p. 66.
- [2] W. H. Bartley, "An Analysis of Transformer Failures, Part 2 — Causes, Prevention and Maximum Service Life," 1998.
- [3] ASTM, "Standard Test Method for Detection and Measurement of Partial Discharge (Corona) Pulses in Evaluation of Insulation Systems," *ASTM D 1868*, 2007.
- [4] ASTM, "Standard Test Method for Dielectric Breakdown Voltage of Insulating Oils of Petroleum Origin Using VDE Electrodes," *ASTM D 1816*, 2004.
- [5] ASTM, "Standard Test Method for Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes," *ASTM D 877*, 2002.
- [6] T. K. Saha, "Review of modern diagnostic techniques for assessing insulation condition in aged transformers," *Dielectrics and Electrical Insulation, IEEE Transactions on [see also Electrical Insulation, IEEE Transactions on]*, vol. 10, pp. 903-917, 2003.
- [7] I. E. Commission, "Insulating Liquids-Oil Impregnated Paper and Pressboard-Determination of Water by Automatic Coulometric Karl Fischer Titration," *Intern. Electrotechnical Commission (IEC)*, 1997.
- [8] A. International, "Standard Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography," *ASTM D 3612*, 2002.
- [9] A.-A. International, "Standard Test Method for Measurement of Average Viscometric Degree of Polymerization of New and Aged Electrical Papers and Boards," *ASTM D 4243*, 1999.04.10 1999.
- [10] ASTM, "Standard Test Method for Furanic Compounds in Electrical Insulating Liquids by High-Performance Liquid Chromatography (HPLC)," *ASTM D5837 - 05*, 2005.
- [11] W. M. Flanagan, "Introduction," in *Handbook of Transformer Design and Applications*: McGraw-Hill Professional, 1993, pp. 1–2.
- [12] Stahlkocher, "Three-Phase, Medium-Voltage Transformer, cut-away view.." vol. 121KB, 2006.

- 
- [13] I. Hohlein and A. J. Kachler, "Aging 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," *Electrical Insulation Magazine, IEEE*, vol. 21, pp. 20-24, 2005.
- [14] A. J. Kachler and I. Hohlein, "Aging of cellulose at transformer service temperatures. Part 1: Influence of type of oil and air on the degree of polymerization of pressboard, dissolved gases, and furanic compounds in oil," *Electrical Insulation Magazine, IEEE*, vol. 21, pp. 15-21, 2005.
- [15] "IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment," *IEEE Std C57.106-2006 (Revision of IEEE Std C57.106-2002)*, pp. 1-36, 2006.
- [16] T. O. Rouse, "Mineral insulating oil in transformers," *Electrical Insulation Magazine, IEEE*, vol. 14, pp. 6-16, 1998.
- [17] A.-A. International, "Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus," *ASTM D 3487*, vol. ASTM D 3487, 2000.11.10 2000.
- [18] Y. Leblanc, R. Gilbert, J. Jalbert, M. Duval, and J. Hubert, "Determination of dissolved gases and furan-related compounds in transformer insulating oils in a single chromatographic run by headspace/ capillary gas chromatography," *Journal of Chromatography A*, vol. 657, pp. 111-118, 1993.
- [19] A. M. Emsley, X. Xiao, R. J. Heywood, and M. Ali, "Degradation of cellulosic insulation in power transformers. Part 2: formation of furan products in insulating oil," *Science, Measurement and Technology, IEE Proceedings -*, vol. 147, pp. 110-114, 2000.
- [20] M. Levin, "Interaction between Insulating Paper and Transformer Oil: Bacterial Content and Transport of Sulfur and Nitrogen Compounds [Feature Article]," *Electrical Insulation Magazine, IEEE*, vol. 24, pp. 41-46, 2008.
- [21] A. M. Emsley and G. C. Stevens, "Review of chemical indicators of degradation of cellulosic electrical paper insulation in oil-filled transformers," *Science, Measurement and Technology, IEE Proceedings-*, vol. 141, pp. 324-334, 1994.
- [22] John Scheirs, Giovanni Camino, Mauro Avidano, and W. Tumiatti, "Origin of furanic compounds in thermal degradation of cellulosic insulating paper," *Journal of Applied Polymer Science*, vol. 69, pp. 2541-2547, 1998.
- [23] P. J. Baird, H. Herman, G. C. Stevens, and P. N. Jarman, "Non-destructive measurement of the degradation of transformer insulating paper," *Dielectrics and*

- 
- Electrical Insulation, IEEE Transactions on [see also Electrical Insulation, IEEE Transactions on]*, vol. 13, pp. 309-318, 2006.
- [24] ASTM, "Standard Test Method for Voltage Endurance of Solid Electrical Insulating Materials Subjected to Partial Discharges (Corona) on the Surface," *ASTM D 2275*, 2001.
- [25] ASTM, "Standard Test Method for Dissipation Factor (or Power Factor) and Relative Permittivity (Dielectric Constant) of Electrical Insulating Liquids," *ASTM D 924*, 2004.
- [26] ASTM, "Standard Test Methods for AC Loss Characteristics and Permittivity (Dielectric Constant) of Solid Electrical Insulation," *ASTM D 150*, 2004.
- [27] P. Osvath, G. Csepes, and M. Webb, "Polarisation Spectrum Analysis for Diagnosis of Insulation System," *6th internl. Conf. Dielectric Materials*, , pp. 270-273, 1992.
- [28] U. Gafvert, L. Adeen, M. Tapper, P. Ghasemi, and B. Jonsson, "Dielectric Spectroscopy in Time and Frequency Domain Applied to Diagnostic of Power Transformers," *Proc. 6th Intern. Conf. Properties and Applications of Dielectric Materials (ICPADM)*, vol. 2., pp. 825-830, 2000.
- [29] S. M. Gubanski, "Dielectric Response Methods -for Diagnostics of Power Transformers-on Behalf of Task Force 15.01.09," *ELECTRA*, vol. 202, pp. 25-36, 2002.
- [30] ASTM, "Standard Test Method for Water in Insulating Liquids by Coulometric Karl Fischer Titration," *ASTM D1533*, 2000.
- [31] M. Duval and A. dePabla, "Interpretation of gas-in-oil analysis using new IEC publication 60599 and IEC TC 10 databases," *Electrical Insulation Magazine, IEEE*, vol. 17, pp. 31-41, 2001.
- [32] R. Blue, D. Uttamchandani, and O. Farish, "Infrared detection of transformer insulation degradation due to accelerated thermal aging," *Dielectrics and Electrical Insulation, IEEE Transactions on [see also Electrical Insulation, IEEE Transactions on]*, vol. 5, pp. 165-168, 1998.
- [33] J. P. Percherancier and P. J. Vuarchex, "Fourier transform infrared (FT-IR) spectrometry to detect additives and contaminants in insulating oils," *Electrical Insulation Magazine, IEEE*, vol. 14, pp. 23-29, 1998.
- [34] S. Itahashi, H. Mitsui, T. Sato, and M. Sone, "State of water in hydrocarbon liquids and its effect on conductivity [transformer oil]," *Dielectrics and*
-

- 
- Electrical Insulation, IEEE Transactions on* [see also *Electrical Insulation, IEEE Transactions on*], vol. 2, pp. 1117-1122, 1995.
- [35] R. Neimanis, H. Lennholm, and R. Eriksson, "Determination of moisture content in impregnated paper using near infrared spectroscopy," 1999, pp. 162-165 vol.1.
- [36] M. J. Shenton, H. Herman, R. J. Heywood, and G. C. Stevens, "The use of spectroscopy with chemometrics to assess the condition and predict the lifetime of paper and oil used as transformer insulation," 2000, pp. 346-351.
- [37] M. K. Pradhan, "Assessment of the status of insulation during thermal stress accelerated experiments on transformer prototypes," *Dielectrics and Electrical Insulation IEEE Transactions*, vol. 13, pp. 227-237, 2006.
- [38] M. Arshad and S. M. Islam, "A Novel Fuzzy Logic Based Power Transformer Condition Assessment Using Oil UV-Spectrophotometry," 2004.
- [39] J. A. Palmer, W. Xianghui, R. A. Shoureshi, A. Mander, D. Torgerson, and C. Rich, "Effect of aging on the spectral response of transformer oil," 2000, pp. 460-464.
- [40] F. Shafizadeh and Y. Z. Lai, "Thermal Degradation of 1,6-Anhydro-B-D-glucopyranose," *J. Org. Chem*, vol. 37, pp. 278-284, May 24, 1972.
- [41] Sergei Levchik, John Scheirs, Giovanni Camino, Wander Tumiatti, and M. Avidano, "Depolymerization process in the thermal degradation of cellulosic paper insulation in electrical transformers," *Polymer Degradation and Stability*, pp. 507-511, 13 February 1997.
- [42] J. R. Sans, K. M. Bilgin, and J. J. Kelly, "Large-scale survey of furanic compounds in operating transformers and implications for estimating service life," in *Electrical Insulation, 1998. Conference Record of the 1998 IEEE International Symposium on*, 1998, pp. 543-553 vol.2.
- [43] A. de Pablo, "Furfural and ageing: how are they related," in *Insulating Liquids (Ref. No. 1999/119), IEE Colloquium on*, 1999, pp. 5/1-5/4.
- [44] I. T. C. No.10, "Unused Hydrocarbon-Based Insulating Liquids-Test Methods for Evaluating The Oxidation Stability " *IEC 61125*, vol. first edition 1992.
- [45] ASTM, "Standard Practices for Sampling Electrical Insulating Liquids," *D 923 - 07*, 2007.
- [46] ASTM, "Standard Practice for Describing and Measuring Performance of Ultraviolet, Visible, and Near-Infrared Spectrophotometers," *ASTM E 275-01*, vol. 03.06, pp. 72-81, 2001.
-

- 
- [47] I. E. Internationale, "Unused hydrocarbon-based insulating liquids-Test methods for evaluating the oxidation stability," vol. 61125, 1992.
- [48] R. S. Gohlke and F. W. McLafferty, "Early gas chromatography/mass spectrometry " *Journal of the American Society for Mass Spectrometry*, vol. Volume 4, pp. 367-371, 1993.
- [49] L.D. Field, S. Sternhell, and J. R. Kalman., *Organic structures from spectra*. Chichester: ohn Wiley and Sons Ltd, 2008.
- [50] Sumario, "Beer lambert," in *png*. vol. 74KB, Beer\_lambert.png, Ed., 2006.
- [51] P. Verma, M. Roy, R. K. Tiwari, and S. Chandra, "Generation of furanic compounds in transformer oil under accelerated thermal and electrical stress," in *Electrical Insulation Conference and Electrical Manufacturing Expo, 2005. Proceedings, 2005*, pp. 112-116.
- [52] John Scheirs, Giovanni Camino, Wander Tumiatti, and M. Avidano, "Study of the mechanism of thermal degradation of cellulosic paper insulation in electrical transformer oil," *Die Angewandte Makromolekulare Chemie*, vol. 259, pp. 19-24, 1998.
- [53] MATLAB, "Fuzzy Logic Toolbox User's Guide," pp. 1-299, 2007.
- [54] "Fuzzy Logic," in *Stanford Encyclopedia of Philosophy*, 2002.
- [55] S. Mofizul Islam, T. Wu, and G. Ledwich, "A novel fuzzy logic approach to transformer fault diagnosis," *Dielectrics and Electrical Insulation, IEEE Transactions on*, vol. 7, pp. 177-186, 2000.

## APPENDIX A: FUZZY LOGIC

The greatest asset of a human's expertise is his or her ability to make a judgment based on imprecise, incomplete and uncertain information. Similarly, fuzzy logic is a new way of representing inaccuracies and uncertainties in data for machine realization. In electrical engineering field, the fuzzy knowledge is developed based on the encapsulation of the expert system's behavior for power transformer and engineers' experienced knowledge.

The term "fuzzy logic" is actually emerged in the development of the theory of fuzzy sets by Lotfi Zadeh in 1965 [54]. In fuzzy logic, a statement is true to various degrees, ranging from the completely true, through half-true to completely false which differs from traditional set theory's true/false approach [55]. In general term, the principal objectives is the treatment of inaccuracies and uncertainties embedded in data by defining a fuzzy set comprising membership functions representing the degree of belonging to the set [55]. This methodology is particularly useful in developing asset management modeling for electrical power systems. For various reasons, many stresses may act simultaneously inside the transformer, increasing its complexity and resulting in the impossibility to develop a precise analytical asset management model [38]. Therefore, fuzzy logic analysis is a favorable approach in this research.

In a more detail definition, take the example of an universe items  $X$  that consist of  $(x_1, x_2, x_3, \dots, x_n)$  and a fuzzy set  $A$  mapped onto it. Let  $\mu_A(x_i)$  be the membership function that maps the element  $x_i$  onto  $X$  to the degree in the range 0 to 1. The fuzzy set  $A$  then can be written as [55]:

$$A = \sum_{i=1}^n \frac{\mu_A(x_i)}{x_i} \quad (\text{i})$$

And, if  $X$  is a continuous function, then [55]

$$A = \int_x \frac{\mu_A(x_i)}{x_i} \quad (\text{ii})$$

In utilizing the above equations for the understanding of fuzzy logic modeling in this research,  $X$  will be a set of transformer diagnostic data (such as UV-Vis spectral

response characteristic), called the universe, whose elements are denoted by  $x$  (such as parameters from UV-Vis spectral response). Furan concentration relationship to UV-Vis spectroscopy will be characterized by the membership in a subset  $A$  (such as furan content) of  $X$ , which is related by the membership function of  $\mu_A$  to  $X$  expressed in the real interval of  $[0,1]$ . Where  $A$  (furan content) is a fuzzy set and is a subset of  $X$  (UV-Vis spectrometry) that has no sharp boundary. The  $\mu_A$  is a grade of membership  $x$  in  $A$ . The closer the value of  $\mu_A$  is to 1, the more  $x$  (parameters from UV-Vis spectrometry) belongs to  $A$  (furan contents). It is therefore indicated by the following equation [38]:

$$A = \{(x, \mu_A(x)), x \in X\} \quad (\text{iii})$$

In addition, the support of the fuzzy set  $A$  in the universal set  $X$  is the crisp set that contains all the elements of  $X$

$$A = \{x \in X | \mu_A(x) > 0\} \quad (\text{iv})$$

With the finite support, let  $x_i$  be an element of the support of fuzzy set  $A$  and  $\mu_A$  a grade of membership in  $A$ , then  $A$  is summarized back to equation (i). The fuzzy logic's degree of membership is then express as [38]

$$Fz[x \in A] = \mu_A(x): \mathfrak{R} \rightarrow [0,1] \quad (\text{v})$$

Where  $A$  is the fuzzy set represented by a membership function, all the elements are denoted by a point  $x$  on the real line  $\mathfrak{R}$ . This will be a mapping of degree of membership value  $\mu$ , lies somewhere on the real interval of 0 to 1 [38].

In fuzzy logic, the most common set of knowledge based linguistic rules are developed on fuzzy IF-THEN rules. Fuzzy IF-THEN rules is normally used on a partial imprecise knowledge on some crisp function and have the form IF  $x$  is  $A_i$  THEN  $y$  is  $B_i$ . It should not be immediately understood as implication; more as a table that relates values of a (dependent) variable  $y$  to values of an (independent variable)  $x$  [54]:

**Table A: Relationship of a (dependent) variable  $y$  to an (independent variable)  $x$**

$x$	$A_1$	...	$A_n$
$y$	$B_1$	...	$B_n$

where  $A_i$ ,  $B_i$  may be crisp (concrete numbers) or fuzzy (small, medium,...). The relationship might be mapped in  $x$ - $y$  surface as below [38]:

$$\mu_{A \rightarrow B}(x, y) = \min[\mu_A(x), \mu_B(y)] \quad (\text{vi})$$

$$\forall_x \in X, \forall_y \in Y \quad (\text{vii})$$

As shown in Table A, for a listing of  $n$  possibilities, called Mamdani's formula (given the interpretation of  $A_i$ 's,  $B_i$ 's and truth functions of connectives) can also be used to develop a Mamdani's model using the following equation [54]:

$$MAMD(x, y) = \bigvee_{i=1}^n [A_i(x) \& B_i(y)] \quad (\text{viii})$$

(where  $x$  is  $A_1$  and  $y$  is  $B_1$  or  $x$  is  $A_2$  and  $y$  is  $B_2$  or...)

$$\text{With} \quad \mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)] \Rightarrow \forall_x \in X \quad (\text{ix})$$

Which  $\mu_{A \cap B}$  is the respective membership function of  $A \cap B$

However, the fuzzy IF-THEN rule is more applicable for the model development of this project. The knowledge based fuzzy rules will be defined in term of input variables (UV-Vis spectrometry's variables) to the fuzzy logic model for an output of transformer oil assessment (furan concentration). Gaussian combination (bell shaped) membership functions are selected for the input fuzzy modeling and triangular membership function is selected for the output of the fuzzy modeling.

The experimental result has indicated that variables available from UV-Vis spectrometry that strongly correlate with furan concentration are spectral bandwidth wavelength and the maximum absorption peaks of the waveform. These two parameters are chosen as input variables for the fuzzy logic model. An example of the rule that developed, based on the equation (vi) is:

$$\mu_{R_i}(a, b, c) = \min[\mu_A(a), \mu_B(b), \mu_C(c)] \quad (\text{x})$$

Means that IF  $a$  (bandwidth) is  $A_i$  and  $b$  (maximum peaks) is  $B_i$ , THEN  $c_i$ (furan content) is  $f_i(a, b)$

A method of defuzzification to convert the fuzzy output into a numerical value for furan concentration is applied by using the centroid method. The centroid or center of gravity method finds the balance point of the solution (fuzzy region) by

calculating the weighted mean of the fuzzy region. The mathematical analysis for defuzzification is as given by [38]:

$$\mathfrak{R} \rightarrow \frac{\sum_{i=0}^n d_i \mu_A(d_i)}{\sum_{i=0}^n \mu_A(d_i)} \quad (\text{xi})$$

Where  $d$  is the  $i$ th domain value and  $\mu(d)$  is the truth membership value for that domain point.

## APPENDIX B: PARAMETERS FOR FUZZY EQUATION

**Table B: Parameters for the 10 sets of fuzzified UV-Vis Absorption Bandwidth input in Gaussian combination membership function**

Set	Name	$\sigma 1$	$c1$	$\sigma 2$	$c2$
1	~348.760	4.000	345.2	4.000	349.3
2	~367.320	3.000	367.3	3.000	367.3
3	~387.300	3.000	387.3	3.000	387.3
4	~401.550	5.393	40.9	5.393	403.3
5	~414.330	5.393	413.5	5.393	415.1
6	~420.390	5.393	419.6	5.393	420.2
7	~434.755	5.393	434.4	5.393	435.2
8	~444.440	5.393	443.5	5.393	445.4
9	~454.795	5.393	453.8	5.393	455.8
10	~470.505	5.393	471.6	5.393	472.0

**Table C: Parameters for the 10 sets of fuzzified UV-Vis maximum absorption peak input in Gaussian combination membership function**

Set	Name	$\sigma 1$	$c1$	$\sigma 2$	$c2$
1	~1.5000	0.010	1.47	0.010	1.48
2	~1.5710	0.007	1.58	0.007	1.58
3	~1.6200	0.007	1.62	0.007	1.62
4	~1.6700	0.010	1.66	0.010	1.70
5	~1.7410	0.010	1.73	0.010	1.75
6	~1.7810	0.010	1.78	0.010	1.78
7	~1.8030	0.010	1.79	0.010	1.81
8	~1.8360	0.010	1.82	0.010	1.85
9	~1.8670	0.010	1.84	0.010	1.92
10	~1.9465	0.010	1.94	0.010	2.00

**Table D: Parameters for the 10 sets of fuzzified furan concentration output in Triangular membership function**

<b>Set</b>	<b>Name</b>	<b><i>a</i></b>	<b><i>b</i></b>	<b><i>c</i></b>
<b>1</b>	New	-1.271	0.100	1.271
<b>2</b>	1.0ppm	1.270	1.290	1.330
<b>3</b>	2.0ppm	1.300	1.782	2.800
<b>4</b>	3.0ppm	2.400	3.000	4.000
<b>5</b>	4.0ppm	3.700	4.000	5.000
<b>6</b>	5.0ppm	6.000	6.500	7.500
<b>7</b>	7.0ppm	6.500	6.900	8.500
<b>8</b>	10.0ppm	9.000	10.160	11.000
<b>9</b>	12.0ppm	11.440	12.710	13.980
<b>10</b>	15.0ppm	14.300	15.240	16.510

**APPENDIX C: IF-THEN RULES**

1. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is new) (1)
2. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 1.0ppm) (1)
3. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 5.0ppm) (0.5)
4. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 10.0ppm) (0.5)
5. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 12.0ppm) (0.5)
6. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 15.0ppm) (0.5)
7. If (MaxPeak is ~1.5) and (bandwidth is ~367.32) then (Furan\_content is 1.0ppm) (0)
8. If (MaxPeak is ~1.5) and (bandwidth is ~401.55) then (Furan\_content is 2.0ppm) (0)
9. If (MaxPeak is ~1.571) and (bandwidth is ~348.76) then (Furan\_content is new) (0)
10. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 2.0ppm) (0)
11. If (MaxPeak is ~1.670) and (bandwidth is ~348.76) then (Furan\_content is new) (0)
12. If (MaxPeak is ~1.670) and (bandwidth is ~367.32) then (Furan\_content is 1.0ppm) (0)
13. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 2.0ppm) (1)
14. If (MaxPeak is ~1.571) and (bandwidth is ~387.3) then (Furan\_content is 2.0ppm) (0)
15. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 3.0ppm) (1)
16. If (MaxPeak is ~1.741) and (bandwidth is ~414.33) then (Furan\_content is 4.00ppm) (1)
17. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 4.00ppm) (0)
18. If (MaxPeak is ~1.781) and (bandwidth is ~414.33) then (Furan\_content is 5.0ppm) (0.01)
19. If (MaxPeak is ~1.781) and (bandwidth is ~434.755) then (Furan\_content is 10.0ppm) (0)
20. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 7.0ppm) (1)
21. If (MaxPeak is ~1.803) and (bandwidth is ~444.44) then (Furan\_content is 10.0ppm) (0)
22. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 1.0ppm) (0)
23. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 2.0ppm) (0)
24. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 5.0ppm) (0)
25. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 10.0ppm) (0)
26. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 12.0ppm) (0)
27. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 15.0ppm) (0)
28. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 3.0ppm) (0)
29. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 4.00ppm) (0)
30. If (MaxPeak is ~1.5) and (bandwidth is ~348.76) then (Furan\_content is 7.0ppm) (0)
31. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 2.0ppm) (0)
32. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 5.0ppm) (0)
33. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 10.0ppm) (0)
34. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 12.0ppm) (0)
35. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 15.0ppm) (0)
36. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 4.00ppm) (0)
37. If (MaxPeak is ~1.571) and (bandwidth is ~367.32) then (Furan\_content is 7.0ppm) (0)
38. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 5.0ppm) (0)
39. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 10.0ppm) (0)
40. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 12.0ppm) (0)
41. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 15.0ppm) (0)
42. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 4.00ppm) (0)
43. If (MaxPeak is ~1.670) and (bandwidth is ~401.55) then (Furan\_content is 7.0ppm) (0)
44. If (MaxPeak is ~1.741) and (bandwidth is ~414.33) then (Furan\_content is 10.0ppm) (0)
45. If (MaxPeak is ~1.741) and (bandwidth is ~414.33) then (Furan\_content is 12.0ppm) (0)
46. If (MaxPeak is ~1.741) and (bandwidth is ~414.33) then (Furan\_content is 15.0ppm) (0)
47. If (MaxPeak is ~1.741) and (bandwidth is ~414.33) then (Furan\_content is 3.0ppm) (0)
48. If (MaxPeak is ~1.741) and (bandwidth is ~414.33) then (Furan\_content is 7.0ppm) (0)
49. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 1.0ppm) (0)
50. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 2.0ppm) (0)
51. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 10.0ppm) (0)
52. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 12.0ppm) (0)
53. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 15.0ppm) (0)
54. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 3.0ppm) (0)
55. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 4.00ppm) (0)
56. If (MaxPeak is ~1.781) and (bandwidth is ~420.39) then (Furan\_content is 7.0ppm) (0)
57. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is new) (0)
58. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 1.0ppm) (0)
59. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 2.0ppm) (0)
60. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 5.0ppm) (0)

61. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 10.0ppm) (0)
62. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 12.0ppm) (0)
63. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 15.0ppm) (0)
64. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 3.0ppm) (0)
65. If (MaxPeak is ~1.803) and (bandwidth is ~434.755) then (Furan\_content is 4.00ppm) (0)
66. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is new) (0)
67. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 1.0ppm) (0)
68. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 2.0ppm) (0)
69. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 5.0ppm) (0)
70. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 12.0ppm) (0)
71. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 15.0ppm) (0)
72. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 3.0ppm) (0)
73. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 4.00ppm) (0)
74. If (MaxPeak is ~1.836) and (bandwidth is ~444.44) then (Furan\_content is 7.0ppm) (0)
75. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is new) (0)
76. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 1.0ppm) (0)
77. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 2.0ppm) (0)
78. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 5.0ppm) (0)
79. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 10.0ppm) (0)
80. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 15.0ppm) (0)
81. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 3.0ppm) (0)
82. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 4.00ppm) (0)
83. If (MaxPeak is ~1.867) and (bandwidth is ~454.795) then (Furan\_content is 7.0ppm) (0)
84. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is new) (0)
85. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 1.0ppm) (0)
86. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 2.0ppm) (0)
87. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 5.0ppm) (0)
88. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 10.0ppm) (0)
89. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 12.0ppm) (0)
90. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 3.0ppm) (0)
91. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 4.00ppm) (0)
92. If (MaxPeak is ~1.9465) and (bandwidth is ~470.505) then (Furan\_content is 7.0ppm) (0)
93. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is new) (0)
94. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 1.0ppm) (0)
95. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 5.0ppm) (0)
96. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 10.0ppm) (0)
97. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 12.0ppm) (0)
98. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 15.0ppm) (0)
99. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 3.0ppm) (0)
100. If (MaxPeak is ~1.62) and (bandwidth is ~387.3) then (Furan\_content is 4.00ppm) (0)

## APPENDIX D: DP ESTIMATION

Based on equation (2-1) [43], the DP can be calculated using the furan concentration available in oil. The DP estimated using furan content value is recorded in Table E. With such simple calculation, DP estimation can also be easily included in the furan content estimation system. The developed model will provide more data for better investigation on the power transformer solid insulation degradation.

**Table E: DP calculation based on equation 2-1**

Furan Content (ppm)	DP calculated	Percentile of deterioration (%)
0	800	<75
0.5	757	
1	719	
2	653	
3	598	
4	551	
5	512	
7	447	87
10	376	96.5
12	340	
13	324	98.5
15	297	>98.5