Department of Electrical and Computer Engineering

A New Technique to Detect Loss of Insulation Life in Power Transformers

Norazhar Bin Abu Bakar

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Declaration

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

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

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Abstract

Power transformer condition monitoring plays an important role in order to maintain the reliability of power systems operations. Failure of a power transformer could lead to a major disaster affecting the whole transmission and distribution network systems. The quality of the insulation system within power transformers comprising dielectric insulation paper and oil reflects the overall health condition of the transformer. The combination of heat (pyrolysis), moisture (hydrolysis) and air (oxidation) within operating transformers causes oil and paper decomposition which result in a number of gases that relate to the cause and effect of various faults. A gas chromatography (GC) instrument is currently used as a laboratory-based technique to quantify dissolved gases in transformer oil samples. However, the GC technique incurs running costs and requires an expert to conduct the test. Furthermore, due to the complexity of the equipment, GC measurement can only performed in a laboratory environment hence takes a long time to get the results. On the other hand, the quality of the insulating oil influences the performance and the service life of the transformer. During the oil aging process, oil gets contaminated with dissolved decay products and sludge as a result of the chemical reaction between the mineral oil molecules and oxygen dissolved in oil. Sludge and contamination development in insulating oil can be identified by measuring the interfacial tension (IFT) value of the oil. The ASTM D971 standard (Interfacial Tension of Oil Against Water by the Ring Method) is widely used to measure IFT of insulating oil. However, this technique is very sensitive and if the precautions mentioned in the standard procedure are not carefully followed may result in an incorrect or inconsistent IFT reading. Moreover, the current technique calls for a trained person to conduct the test that requires a relatively expensive piece of equipment and lengthy time to get the results as oil samples have to be sent to an external laboratory which also incurs an additional running cost.

This thesis proposes an alternative method of measuring the IFT and dissolved gases in transformer oil using absorption spectroscopy which can be performed instantly on-site and has the potential to be implemented on-line. Two novel methods were developed: measuring transformer oil IFT using ultraviolet-to-visible (UV-Vis) spectroscopy, and detecting dissolved gases in transformer oil using near-infrared-to-infrared (NIR-IR) spectroscopy. Also, a new fuzzy logic approach to provide a proper asset management decision and predict the remaining operational life of a power transformer based on some routine insulating oil tests such as furan, dissolved gas analysis (DGA), IFT, water content, and operating temperature has been proposed in this thesis.

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List of Publications

It is acknowledged that most of the work in this thesis has been published in the following papers.

Journals Published

- Norazhar Abu Bakar; A. Abu-Siada ; S. Islam; M. El-Naggar, "A New Technique to Measure Interfacial Tension of Transformer Oil using UV-Vis Spectroscopy", IEEE Transactions on Dielectrics and Electrical Insulation, vol. 22, Issue 2, pp. 1275-1282, April 2015.
- Norazhar Abu Bakar and A. Abu-Siada "A Novel Method of Measuring Transformer Oil Interfacial Tension Using UV-Vis Spectroscopy" IEEE Electrical Insulation Magazine", vol. 32, no. 1, pp. 7-13, Jan 2016.
- Norazhar Abu Bakar, A. Abu-Siada, and S. Islam "A Review of DGA Measurement and Interpretation Techniques" IEEE Electrical Insulation Magazine", vol. 30, no. 3, pp. 39-49, April 2014.
- Norazhar Abu Bakar, A. Abu-Siada, N. Das and S. Islam "Effect of Conducting Materials on UV-Vis Spectral Response Characteristics", Universal Journal of Electrical and Electronic Engineering, vol. 1, no. 3, pp. 81-86, October, 2013.

Journal Submitted

- Norazhar Abu Bakar; A. Abu-Siada, "Fuzzy Logic Approach for Transformer Remnant Life Prediction and Asset Management Decision", Submitted on March 2016 to IEEE Transactions on Dielectrics and Electrical Insulation (accepted for publication on 11th July 2016).
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Conference Papers

- Norazhar Abu Bakar; A. Abu-Siada, S. Islam "A Novel UV-Vis Spectroscopy Application to Measure Interfacial Tension of Transformer Oil", 2015 IEEE PES General Meeting, July 26-30, 2015 Denver, Colorado, USA.
- Norazhar Abu Bakar, A. Abu-Siada, S.Islam, M. F. El-Naggar, "Effects of Various Transformer Oil Contaminations on Its Spectral Response" proceedings of the International Conference on Condition Monitoring and Diagnosis (CMD2014), 21-25 Sept 2014, Jeju, Korea.
- Norazhar Abu Bakar, A. Abu-Siada and S. Islam, "A Review of Chemical Diagnosis Techniques for Transformer Paper Insulation Degradation", proceedings of the Australasian Universities Power Engineering Conference , AUPEC'13, Hobart, 29 Sep.-3 Oct., 2013.
- Norazhar Abu Bakar, A. Abu-Siada, "High Voltage Power Transformer Dissolved Gas Analysis, Measurement and Interpretation Techniques", invited paper, High Voltage Maintenance Forum, Perth, 27-28 November 2013.
- Norazhar Abu Bakar, A. Abu-Siada, "High Voltage Power Transformer Paper Insulation Assessment Techniques", invited paper, High Voltage Maintenance Forum, Perth, 27-28 November 2013.

Conference Submitted Papers

- Norazhar Abu Bakar, Huize Cui, A. Abu-Siada, and Shengtao Li, "A Review of Spectroscopy Technology Applications in Transformer Condition Monitoring", proceedings of the International Conference on Condition Monitoring and Diagnosis (CMD2016), 25-28 Sept 2016, Xi'an, China (accepted for presentation).
- Norazhar Abu Bakar, A. Abu-Siada, "Remnant Life Estimation and Transformer Asset Decision Based on UV-Vis Spectral Response", proceedings of the International Conference on Electrical Machine (ICEM'2016), 4-7 Sept 2016,Lausanne, Switzerland (accepted for presentation).

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List of Abbreviations

2-ACF	2-Acetlyfuran
2-FAL	2-Furan
2-FOL	2-Furfurol
5-HMF	5-Hyroxy Methyl-2-furfural
5-MEF	5-Methyl-2-furfural
ABS	Peak Absorbance
ASTM	American Society for Testing and Materials
BDV	Average Breakdown Voltage
BW	Bandwidth
C_2H_2	Acetylene
C_2H_4	Ethylene
C_2H_6	Ethane
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COG	Centre of Gravity
DGA	Dissolved Gas Analysis
DP	Degree of Polymerization
FT	Fourier Transforms
FRA	Frequency Response Analysis
GC	Gas Chromatography

H_2	Hydrogen
HITRAN	High-resolution Transmission Molecular Absorption Database
HPLC	High-Performance Liquid Chromatography
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFT	Interfacial Tension
IR	Infrared
MeOH	Methanol
MF	Membership Function
M/DW	Moisture per Dry Weight
N_2	Nitrogen
NIR	Near-Infrared
NIST	National Institute of Standards and Technology, United States
O_2	Oxygen
PAS	Photo-Acoustic Spectroscopy
TDCG	Total Dissolved Combustible Gas
UV	Ultraviolet
Vis	Visible

Chapter 1 Introduction

1.1 Background and Motivation

A power transformer is a vital link for any electrical transmission and distribution network, as shown in Figure 1-1. Failure of power transformers could lead to a major disaster affecting the whole power delivery system. Furthermore, an unexpected failure of power transformers could not only cause an electricity shortage to the consumer, but also would involve the loss of millions of dollars for utility companies, industrial failure costs, environmental hazards costs due to oil spillage, and also indirectly to the national security [1]. Based on a report provided in 2003 by the International Association of Engineering Insurers (IMIA), the total losses in five years (from 1997 to 2001) for 94 cases involving power transformer failure, which does not includes Business Interruption claims, was about $286 million [2]. The highest cost was caused by transformer insulation failure, as shown in Table 1-1.

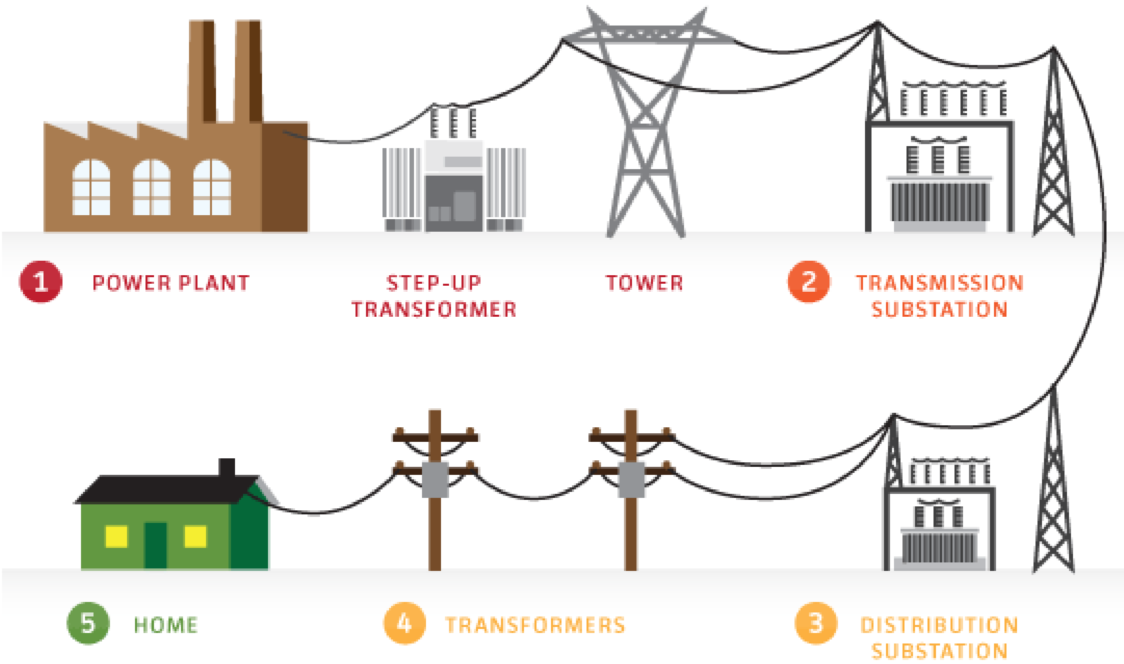

Figure 1-1 Transformers In a Power Delivery System

Another consideration is that, most transformers nowadays are operating either close to or in excess of their design life which is approximately between 35 to 40 years. In fact, the statistics data published by US Department of Energy (2014) shows that the average length of operation of power transformers in the United State is approximately 40 years [1].

Table 1-1 Transformer Causes of Failure and Losses [2]

Cause of Failure	Number	Total Cost
Insulation Failure	24	$149,967,277
Design/ Material/ Workmanship	22	$64,696,051
Unknown	15	$29,776,245
Oil Contamination	4	$11,836,367
Overloading	5	$8,568,768
Fire/ Explosion	3	$8,045,771
Line Surge	4	$4,959,691
Improper Maintenance/ Operation	5	$3,518,783
Flood	2	$2,240,198
Loose Connection	6	$2,186,725
Lightning	3	$657,935
Moisture	1	$175,000
	94	$286,628,811

Meanwhile, according to Western Power Australia, in their State of Infrastructure Report 2014/15, the majority of transformers operated in Western Australia are over 30 years old and 11.1% of them are already over 40 years old, as shown in Fig.1-2 [3]. A failure rates analysis in accordance with the transformer failure pattern "bathtub" curve reveals that the possibility of a power transformer failure is increased after 30 years of service, as shown in Figure1-3 [2, 4].

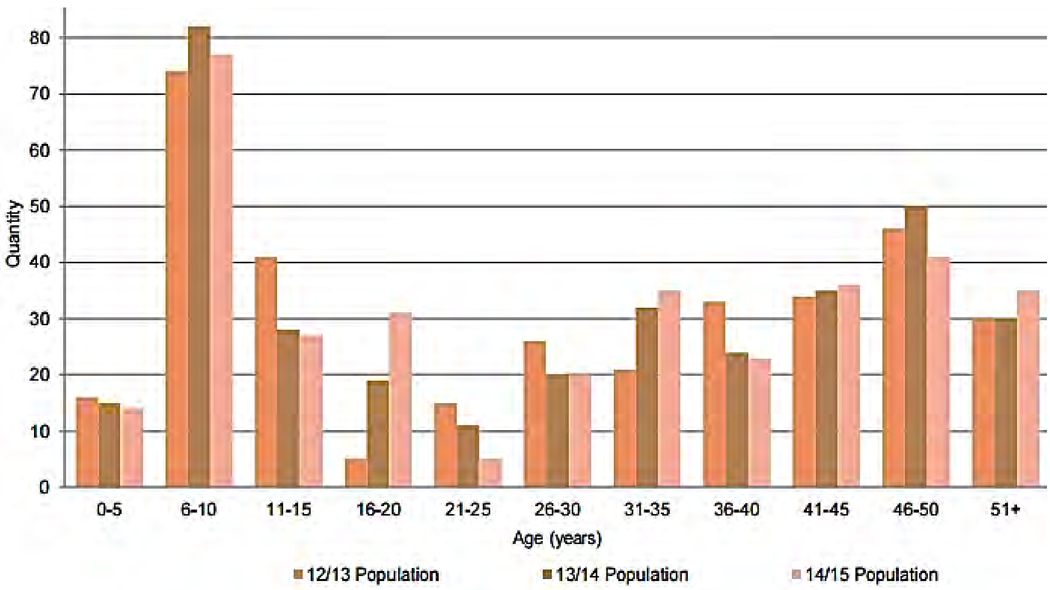

Figure 1-2 Power Transformer Population in Western Australia [3]

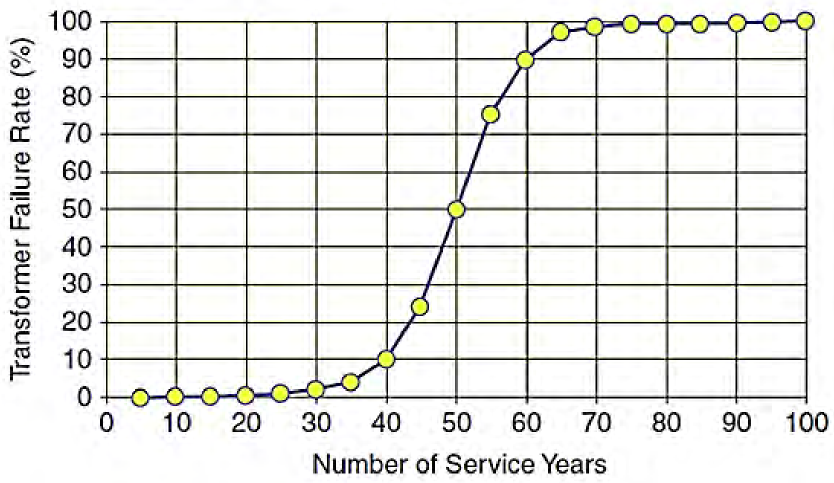

Figure 1-3 Transformer Failure Rates Based on Years of Service [2]

Therefore, a reliable monitoring and diagnostic technique to detect transformer incipient faults is required to avoid catastrophic failures and help in providing efficient predictive maintenance that improves the reliability of the equipment [5]. Often, power transformer health is referred to the quality of its insulation system which consists of paper insulation immersed in insulating oil [6, 7]. Long term degradation of an insulation system occurs mainly through heating (pyrolysis), moisture ingress (hydrolysis) and air ingress (oxidation) [8, 9]. Incipient faults within a transformer can be detected by analyzing samples of its insulating oil, e.g., using dissolved gas analysis and furan analysis [10]. Concurrently, sludge and acids formed in transformer oil affects its quality and potentially increases the rate of insulation paper aging [11]. Thus, IFT and acid number measurements may use as early warnings of insulation aging development [12].

1.2 Research Problem

Several diagnostic techniques have been implemented by industries to assess and monitor the condition of insulation systems of in-service transformers. These assessments can be classified into two groups, electrical and chemical analysis as shown in Fig.1-4. Partial discharge analysis, dielectric breakdown voltage, power factor, time domain polarization, and frequency domain polarization are part of electrical analysis, while water content, acidity, interfacial tension (IFT), degree of polymerization, dissolved gas analysis (DGA), and furan analysis are part of chemical analysis. In practice, water content, acidity, IFT, DGA and furan of transformer insulation oil are frequently monitored during routine maintenance tests, at least once a year for healthy transformers. Meanwhile, for aging or critical transformers, the tests are carried out more frequently.

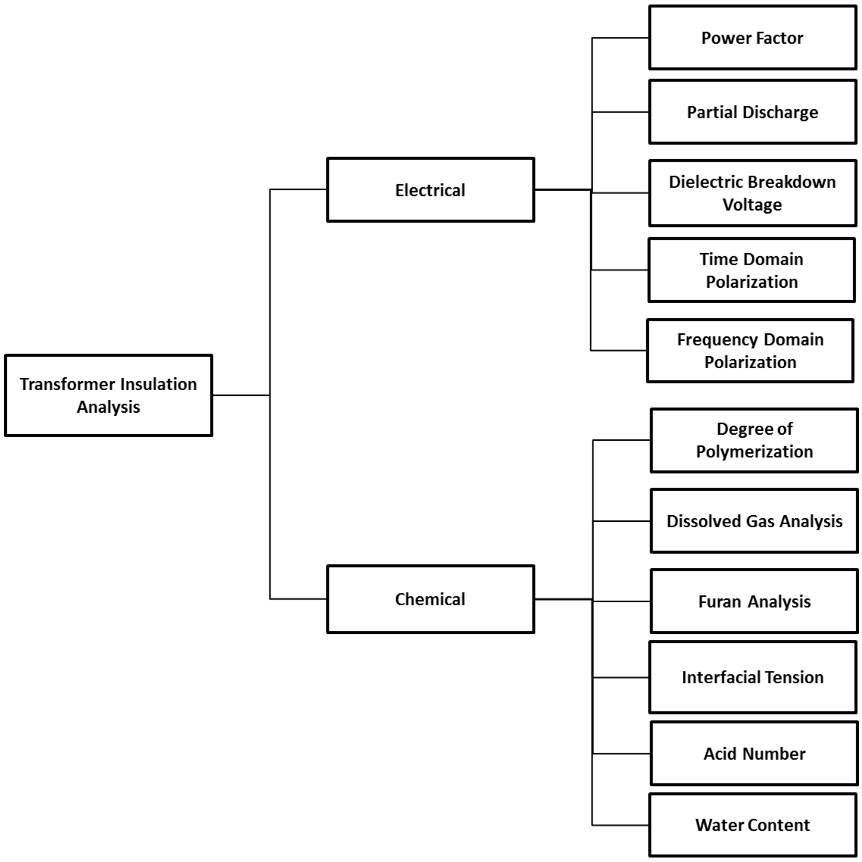

Figure 1-4 Transformer Insulation Analysis

This research is focused on improving the method for diagnoses of the DGA and IFT of transformer insulating oil. Transformer remnant life and asset management decisions based on routine insulating oil testing is also covered in this research. The ASTM D971 standard (Interfacial Tension of Oil against Water by the Ring Method) is widely used to measure the IFT of insulating oil [13].

Soluble polar contaminants and degradation products affect the physical and electrical properties of the insulating oil, thereby lowering the IFT value [13, 14]. The current IFT measurement technique requires great care. Wrong or inconsistent data are likely to be obtained if the precautions mentioned in ASTM D971 standard [13] are not carefully and completely observed. A trained person is required to take the measurements, using an expensive piece of equipment, so that in nearly all cases the oil samples have to be sent to an external laboratory.

On the other hand, gases dissolved in transformer oil can be extracted using ASTM D3612 – Test Method for Analysis of Gases Dissolved in Electrical Insulating Oil by Gas Chromatography [15] or IEC Standard 567- Guide for The Sampling of Gases and of Oil From Oil-Filled Electrical Equipment and For The Analysis of Free and Dissolved Gases.

Current DGA measurement using gas chromatography (GC) can only be done in a laboratory environment due to the complexity of the equipment required where oil samples are to be collected from operating transformers, and transported to the laboratory for gas extraction and measurement processes as stated in ASTM D3612 [15]. Due to the time and costs involved with GC, DGA analysis using this technique is only performed once a year for operating transformers. Frequent DGA testing is only used when significant fault gases have been detected during routine analysis [16].

To overcome the limitation of GC, several new analytical techniques have been introduced, such as the hydrogen on-line monitor and the photo-acoustic spectroscopy (PAS) [16, 17]. Even though both techniques can be implemented on-line, the hydrogen on-line monitor is only capable of detecting a few dissolved gases in transformer oil, whereas the PAS is capable of accurately detecting the gas concentration levels that are influenced by the external temperature and pressure and also affected by vibrations.

In the meantime, the absorption spectroscopy technique which utilizes an electromagnetic effect to determine the energy level and structure of atomic or molecular substance has also been considered for suitability in analysing transformer conditions. Recently, several types of analysis of transformer conditions using absorption spectroscopy techniques have been proposed, such as to analyse the degradation of paper insulation, to estimate the furan concentration in transformer oil, to detect additives and contaminants in insulating oil, and to determine moisture content in insulating oil [18-21]. On the other hand, spectroscopy technologies have also been used to trace the amount of gases concentration either in space or solvent in astrophysics and chemistry fields [22, 23].

1.3 Aim and Objectives

The key aim of this research is to develop a novel reliable cost effective technique to assess the insulation condition of power transformers. The research objectives are listed below:

Objective 1 (a) Investigating the correlation between interfacial tension, acidity, breakdown voltage and water content of transformer oil with its UV-Vis spectral response.
(b) Developing a new technique to measure the interfacial tension of transformer oil using UV-Vis spectroscopy.

Objective 2 (a) Investigating the characteristic of each key gas dissolved in the transformer oil with its NIR-IR spectral response.
(b) Developing a new technique to measure key gases dissolved in transformer oil using NIR-IR spectroscopy.

Objective 3 Developing an expert model to estimate the remnant life and asset management decision of power transformers based on routine insulating oil tests.

1.4 Research Methodology

In respect of the objectives of this research project, the following methodologies are adopted:

- Method for Objective 1: Developing a new technique to measure the interfacial tension of transformer oil using UV-Vis spectroscopy:
  - New and in-service transformer oil collected from utility companies are tested with interfacial tension, acidity, breakdown voltage, and water content in accordance with the current practice standards.
  - Same oil samples are then examined using UV-Vis spectroscopy.
  - The correlation between interfacial tension, acidity, breakdown voltage and water content of transformer oil with its UV-Vis spectral response are investigated.
  - Spectral response results for various interfacial tension numbers are analysed, and the impact of absorbance level and maximum bandwidth are evaluated.
  - The correlation between absorbance level and bandwidth, with the interfacial tension of transformer oil is developed using the fuzzy logic model.
  - The accuracy of the fuzzy logic model developed is validated with other sets of in-service transformer oil.
  - The oil spectroscopy test procedure in this work is conducted in accordance with ASTM E275 [148].

- Method for Objective 2: Developing a new technique to measure the dissolved gases in transformer oil using NIR-IR spectroscopy:
  - Different concentrations of individual key gases dissolved in oil are prepared using new oil in accordance with ASTM D3612 [15] standard and measured with gas chromatography.
  - Same oil samples are then examined using NIR-IR spectroscopy.
  - Spectral response results for each gas with various concentrations are analysed, and the impact of absorbance level and spectral response area in a particular range are evaluated.
  - The correlation between the absorbance level and the spectral response area, with the individual key gases in transformer oil are developed using the fuzzy logic model.