TABLE OF CONTENTS

6 CONCLUSION

ABSTRACT

The power transformer is one of the main components in a power transmission network. Major faults in these transformers can cause extensive damage which does not only interrupt electricity supply but also results in large revenue losses. Thus, these transformers are needed to be routinely maintained. Due to the large number of transformers of different makes and capacities, routine maintenance and diagnosis of such transformers are rather difficult as different transformers exhibit different characteristics and problems. Moreover, different climatic and operating conditions may not be able to draw correct conclusion to some problems. In Malaysia, the lack of local expertise makes dependency on foreign consultants imminent which are rather expensive. To help in overcoming such problems, a Software for Intelligent Diagnostics of Power Transformers known as ADAPT, using the technique of fuzzy logic is developed in this study. The technique allows the interpretation of the Dissolved Gas Analysis (DGA) to be performed routinely on the transformers. In order to ensure that all the transformers are diagnosed and maintained properly, a new intelligent diagnostic architecture known as Total Intelligent Diagnostic Solution (TIDS) has been developed to improve the diagnosis accuracy of the conventional DGA approaches. The TIDS structure has a main interpretation module which consists of Fuzzy TDCG and Fuzzy Key Gases and a supportive interpretation module which consists of Fuzzy Rogers Ratio and Fuzzy Nomograph. The TIDS structure is incorporated into the ADAPT software which allows for multiple diagnostic methods to reach an ultimate outcome especially when verified by four methods. This new architecture leads to the diagnostic of a wider range of transformer fault types and provides a more detail information about the transformer condition, thus help to reduce maintenance costs, prevent unnecessary force outages and avoid explosion danger.

ABSTRAK

Transfomer kuasa merupakan satu komponen penting dalam rangkaian penghantaran kuasa. Kesilapan utama *transfomer* akan menyebabkan kerosakan yang teruk, yang mana bukan sahaja mengganggu bekalan elektrik, malah menyebabkan kerugian yang sangat besar. Oleh sebab itu, kesemua *transformer* ini perlu diselenggarakan pada masa berkala tertentu. Memandangkan sejumlah besar *transfomer* mempunyai pembuatan dan keupayaan yang berbeza, penyelenggaraan dan diagnosis rutin adalah agak sukar kerana *transfomer* yang berlainan menunjukkan ciri dan masalah yang berbeza. Lagipun, cuaca dan keadaan operasi yang berbeza mungkin menyebabkan kesimpulan tepat tidak dapat diperolehi. Di Malaysia, kekurangan pakar tempatan menyebabkan pergantungan kepada perunding asing yang agak mahal. Demi mengatasi masalah ini, satu perisian cerdik untuk mendiagnosis *transfomer* kuasa yang dikenali sebagai ADAPT menggunakan teknik *fuzzy logic* telah dibangunkan dalam projek ini. Teknik ini membenarkan interpretasi *Dissolved Gas Analysis* (DGA) dijalankan secara rutin pada *transfomer*. Untuk menjamin semua *transfomer* didiagnosis dan diselenggarakan dengan sempurna, satu senibina diagnostik cerdik yang baru dikenali sebagai *Total Intelligent Diagnostic Solution* (TIDS) telah dibangunkan untuk meningkatkan ketepatan diagnosis DGA biasa. Struktur TIDS menpunyai satu modul interpretasi utama yang mengandungi *Fuzzy* TDCG dan *Fuzzy Key Gases* dan satu modul interpretasi sokongan yang merangkumi *Fuzzy Rogers Ratio* dan *Fuzzy Nomograph*. TIDS digabungkan dengan perisian ADAPT yang membolehkan pelbagai kaedah diagnosis untuk mencapai satu keputusan muktamad terutamanya keputusannya ditentusahkan oleh empat kaedah. Senibina baru ini mampu mengecam lebih banyak kesalahan dan memberikan maklumat yang lebih teliti tentang keadaan *transfomer*, ini seterusnya mengurangkan kos penyelenggaraan, mengelakkan kuasa tergendala dan mengelakkan letupan berbahaya.

CHAPTER I

INTRODUCTION

1.1 Project Overview - Background of Fault Diagnosis of Power Transformer

The power transformer is a major apparatus in an electrical power network, and its correct functioning is vital to the network operations. In Malaysia there are over one thousand power transformers in service by Tenaga Nasional Berhad (TNB), which is the nation's electricity utility company. Over the years, condition monitoring and periodical analysis of the various gases in these transformers have helped to identify incipient or potential faults in them where the necessary preventive maintenance can be carried out by the TNB maintenance team. This is required as transformers are highly expensive and failure in these transformers may result in the disruption of the power supply to industries as well as consumers which could result in substantial amount of revenue losses for TNB. Thus, preventive techniques for early fault detection in these transformers to avoid outages are rather valuable. As an example of fault occurring in transformers, on 13th March 2000 (The Star, 13 Mac 2000) [2], a transformer of a transmission main intake sub station at the 7km of Jalan Meru, Klang exploded and caught fire. Figures 1.1 and 1.2 show the photographs of the explosion incident in Klang (Sin Chew Jit Poh, 13 Mac 2000) [3]. This case had caused a power disruption to about 20,000 consumers in Meru, part of Kapar, Bukit Rajah and part of Klang town and estimated damage to cost several hundred thousands of ringgit.

Figure 1.1: Example of a transformer explosion at a TNB sub station - 1

Figure 1.2: Example of a transformer explosion at a TNB sub station - 2

Another example of fault in a transformer occurring in Malaysia is shown in Figure 1.3. The photograph shows faulty switchgear or a circuit breaker connected to a transmission power transformer with a connection to a distribution transformer. This fault is called as flashover and it happens when there is a malfunctioning in the transmission transformer caused by an over current. Normally, when this situation occurs, the circuit breaker should be able to isolate the fault by not allowing the current to be transmitted to the distribution transformer. However, for this case the circuit breaker was unable to function properly and as a result the circuit breaker exploded and TNB had to spent million of dollars [4] in order to repair both the transformer and the circuit breaker.

Figure 1.3: Consequence of transformer failure

In daily operation, the power transformer is fully utilized in stepping up or stepping down electrical power for transmission and distribution. Due to the need for continuous demand of electricity, these transformers will not stop operating except when faults occur in them or during maintenance. Because of this factor, we usually spend a lot of money for the maintenance of the transformers to ensure that they are in good operating conditions. However, the transformer is usually subjected to thermal and electrical stresses when operated over a long period of time. These stresses could break down the insulating material and release gaseous decomposition products, which if excessive could cause explosion and, therefore, should be avoided.

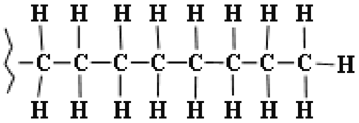
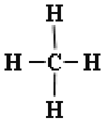
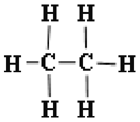
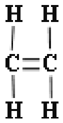
Presently, with the emergence of new technologies and new findings from researchers around the world, there are a variety of diagnostic methods for detecting and predicting the condition of the power transformers. An IEEE standard (C57.104-1991) [5] introduced the Dissolved Gas Analysis (or the DGA method as it is commonly known) as one of the most accepted methods for detecting incipient fault conditions in power transformers. The correlation between the DGA and the corresponding fault conditions in the transformers has been well established and formulated over the past two decades [6]. From the DGA test results, appropriate actions can then be taken to either carry out preventive maintenance or repairs the transformer.

In some countries where there is a lack in local expertise to interpret difficult or inconclusive DGA test results, such as that in Malaysia, foreign expertise is sought. The test results of these transformers are sent to the original manufacturer for a more accurate analysis, however, usually at high expense. In order to overcome such high cost in the interpretations of test results, there have been substantial efforts in developing intelligent diagnostic software or expert systems in this area by utility companies.

1.2 The Dissolved Gases Analysis (DGA) Methodology

Major power transformers are filled with oil that serves several purposes. The oil acts as a dielectric media which is an insulator and as a heat transfer agent. Normally, the insulated oil fluids are composed of saturated hydrocarbons called paraffin, whose general molecular formula is C_nH_{2n+2} with n in the range of 20 to 40 while the cellulose insulation material is a polymeric substance whose general molecular format is $[C_{12}H_{14}O_4(OH)_6]_n$ with n in the range of 300 to 750 [7]. These molecules are connected and linked together to form a chain-liked manner by hydrogen and carbon. The structured formula of the insulating oil is shown in Table 1.1 [7].

Table 1.1: Chemical structure of insulating oil and fault gases

Gases	Chemical Structure
Mineral Oil / Paraffin C_nH_{2n+2}	
Hydrogen H_2	$H-H$
Methane CH_4	 $H-\overset{\overset{H}{\vert}}{\underset{\underset{H}{\vert}}{C}}-H$
Ethane C_2H_6	 $H-\overset{\overset{H}{\vert}}{\underset{\underset{H}{\vert}}{C}}-\overset{\overset{H}{\vert}}{\underset{\underset{H}{\vert}}{C}}-H$
Ethylene C_2H_4	 $\overset{\overset{H}{\vert}}{\underset{\underset{H}{\vert}}{C}}=\overset{\overset{H}{\vert}}{\underset{\underset{H}{\vert}}{C}}$
Acetylene C_2H_2	$H-C\equiv C-H$
Carbon Dioxide CO_2	$O=C=O$
Carbon Monoxide CO	$C\equiv O$
Oxygen O_2	$O=O$
Nitrogen N_2	$N\equiv N$

During normal use, there is usually a slow degradation of the mineral oil to yield certain gases that dissolves in the oil. However, when an electrical fault happens inside the transformer, the oil starts to degrade and temperature will rise abnormally which generates various fault gases at a rapid rate. Different patterns of gases are generated due to the different intensities of energy dissipated according to the types of faults. This phenomenon happens mainly due to the broken chain of the chemical structure of the insulating oil. As a result, the broken-chain molecule will form an individual chemical structure which is known as hydrocarbon gases or fault gases. The cause of the dissipation of the fault gases can be divided into 3 categories which are corona or partial discharge, pyrolysis or thermal heating and arcing. Among the 3 common fault cases, the most severe intensity of energy dissipation occurs with arcing, less with thermal heating and least with corona. Figure 1.4 illustrates the process of breaking chain within the insulating oil chemical structure of the fault arcing, thermal heating, corona and pyrolysis of cellulose.

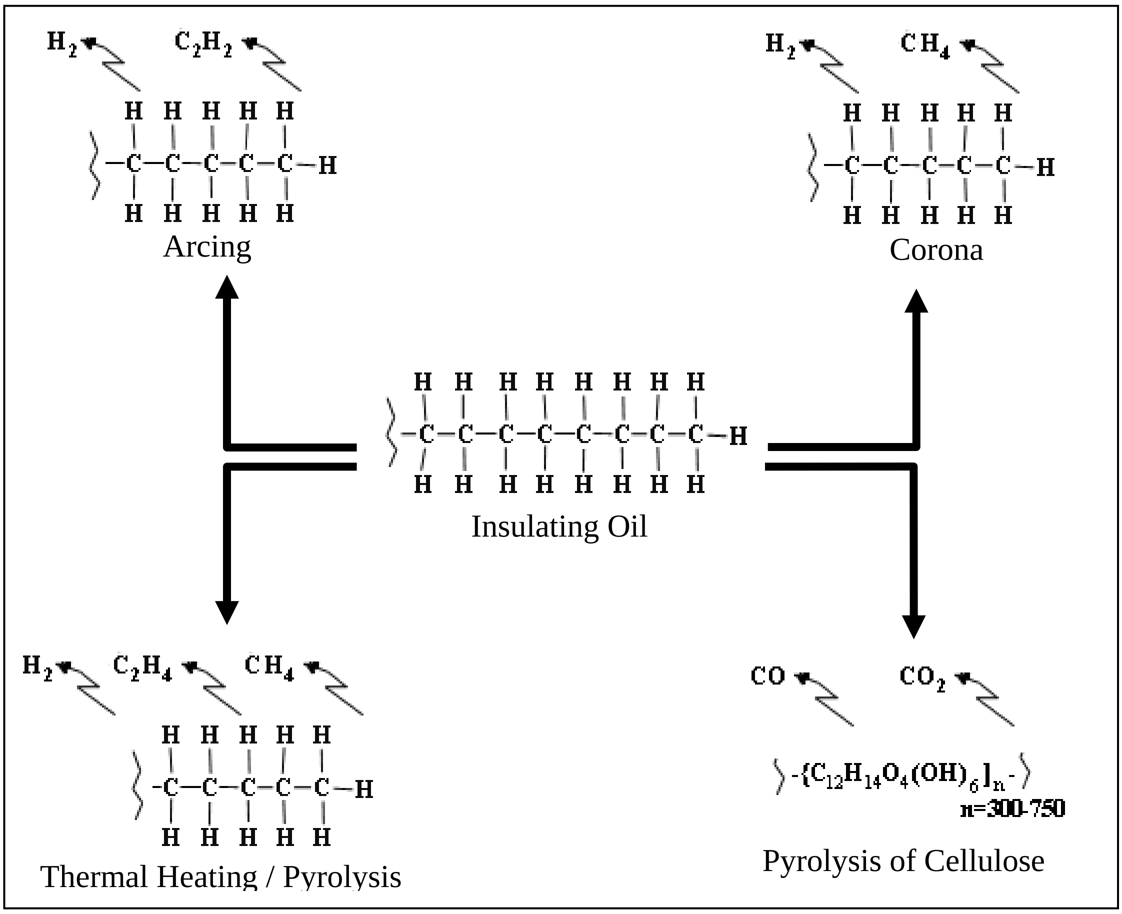


Figure 1.4: Breaking chain process of fault arcing, corona, thermal heating and pyrolysis of cellulose

Gases which are produced by the degradation of oil as a result of elevated temperatures may be caused by several factors as listed below [8]:

- severe overloading
- lighting
- switching transients
- mechanical flaws
- chemical decomposition of oil or insulation
- overheated areas of the windings
- bad connections which have a high contact resistance

The type of gases present in an oil sample makes it possible to determine the corresponding type of fault that occurs in the transformer. This is usually done by analyzing the type and amount of the gases that are present when abnormality occurs or during routine maintenance. The characteristic of the transformer faults are described as below [9]:

- Arcing

  Arcing is the most severe of all fault processes. Large amount of hydrogen and acetylene are produced, with minor quantities of methane and ethylene. Arcing occurs in high current and high temperature conditions. Carbon dioxide and carbon monoxide may also be formed if the fault involved cellulose. In some instances, the oil may become carbonized.

- Thermal heating / Pyrolysis

  Decomposition products include ethylene and methane, together with smaller quantities of hydrogen and ethane. Traces of acetylene may be formed if the fault is severe or involves electrical contacts.

- Corona

  Corona is a low-energy electrical fault. Low-energy electrical discharges produce hydrogen and methane, with small quantities of ethane and ethylene. Comparable amounts of carbon monoxide and dioxide may result from discharge in cellulose.

- Overheated Cellulose

  Large quantities of carbon dioxide and carbon monoxide are evolved from overheated cellulose. Hydrocarbon gases, such as methane and ethylene, will be formed if the fault involved is an oil-impregnated structure.

The Dissolved Gas Analysis or DGA method involves sampling of the oil inside the transformer at various locations. Then, chromatographic analysis will be carried out on the oil sample to measure the concentration of the dissolved gases. The extracted gases are then separated, identified and quantitatively determined such that the DGA method can then be applied in order to obtain reliable diagnosis [6]. The extracted gases meant for analysis purpose are Hydrogen (H_2), Methane (CH_4), Ethane (CH_6), Ethylene (C_2H_4), Acetylene (C_2H_2), Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen (N_2) and Oxygen (O_2). These fault gases can be classified into 3 groups which are shown in Table 1.2.

Table 1.2 : Fault gases group

Group	Hydrocarbons and Hydrogen	Carbon Oxides	Non-fault gases
Gases	CH_4, H_2, CH_6, C_2H_4, C_2H_2	CO, CO_2	N_2, O_2

Depending on the concentration of the dissolved gases, the condition of the transformer can be determined. This is because each type of fault burns the oil in a different way which correspondingly generate different pattern of gases. This makes it possible for experts to identify the nature of the fault type based on the gas type and its concentration. For example, arcing may cause high concentration of acetylene dissolved in the oil. The detail of fault type and the relation with the fault gases can be shown in Table 1.3.

Table 1.3: Relation between fault type and fault gases

Fault	Material Involved	Fault Gases Present
Corona / Partial Discharge	Oil	H_2
	Cellulose	H_2, CO, CO_2
Thermal Heating / Pyrolysis	Oil – Low Temp	CH_4, C_2H_6
	Oil – High Temp	C_2H_4, H_2 (CH_4, C_2H_6)
	Cellulose – Low Temp	CO_2 (CO)
	Cellulose – High Temp	CO (CO_2)
Arcing	Oil/Cellulose	C_2H_2, H_2 (CH_4, C_2H_6, C_2H_4)

There are a number of DGA method available which include the Key Gas Analysis, Rogers Ratio method, Total Dissolved Combustible Gas (TDCG) method, Logarithmic Nomograph method, Doernenberg Ratio method, Duval method, etc [7]. All these methods are quite similar where different patterns and concentration of gases are matched with the characteristic of fault types. Among these methods, the Key Gas method and Rogers Ratio method are the most popular. The Key Gas method employs rules to diagnose abnormalities such as thermal, corona or arcing problems while Rogers Ratio method published by Ron Rogers in 1974 from the Central Electric Generating Board (CEGB) uses four digit different ratio codes to determine the corresponding fault. The TDCG method detects the total combustible fault gases (Hydrogen, Acetylene, Ethane, Methane, Ethylene and Carbon Monoxide) and employs rules to determine the transformer condition. Other diagnostic method like Doernenberg Ratio method uses two ratios of gases to plot on logarithmic axes as shown in Figure 1.5 to indicate the type of faults.

In this research, four most popular DGA diagnostic methods has been applied such as Rogers Ratio method, Key Gas method, TDCG and Logarithmic Nomograph method to form a Total Intelligent Diagnostic Solution (TIDS). The combination of this technique should ensure a more accurate and a more reliable outcome. Details of these methods are described in Chapter 2.

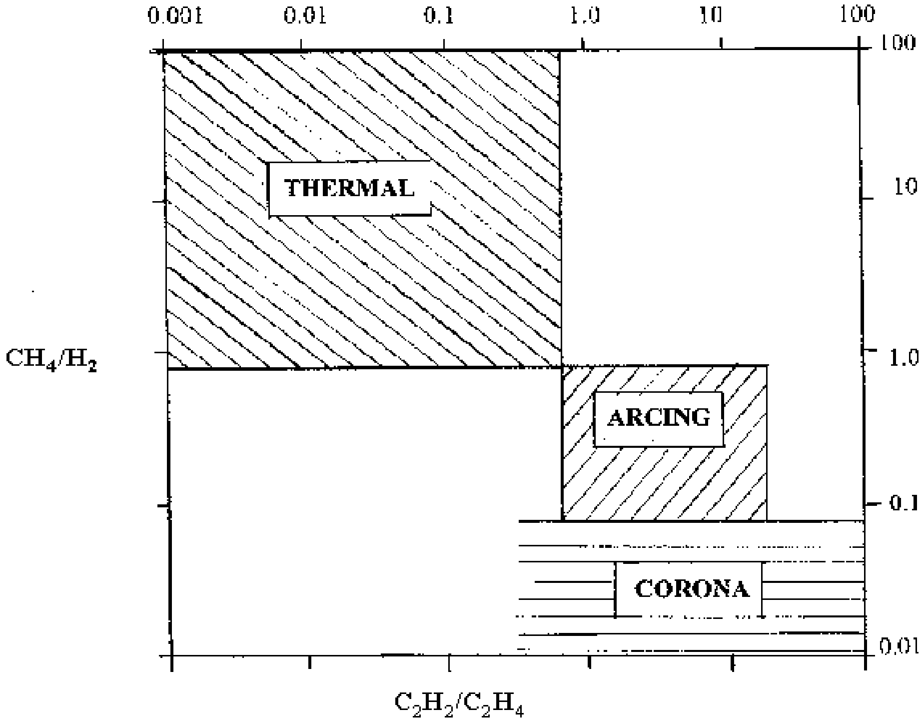


Figure 1.5: Dornenburg plot

1.3 Motivation of Research

DGA is widely accepted as the most reliable technique for the earliest detection of incipient faults in transformers. Nowadays, with the emergence of new technologies and new findings from many researchers around the world, there are a variety of diagnostic methods for detecting and predicting the condition of the power transformers. The following paragraphs describe briefly some of these research works.

Dukarm [8] from the Delta-X Research has published a paper on how fuzzy logic and neural networks can be used to automate the DGA method in fault diagnosis. In this paper, the researchers used the Key Gas Analysis with fuzzy logic and the Fuzzy Rogers Ratio method to diagnose certain faults in transformers. The Key Gas Analysis with fuzzy logic can solve the problem when the input gas value fall within the expected range, however, if it falls outside the expected interval the interpretation will be inconclusive or unknown. Thus, the above method is only able to detect a limited type of fault conditions. Besides, fault detection rules are needed to be determined correctly beforehand based on the configuration of the transformer. Another related research work was done by Zhang, Ding and Liu [10] from The Bradley Department of Electrical Engineering, Virginia Tech, USA. They presented an Artificial Neural Network (ANN) approach to diagnose and detect faults in oil-filled power transformers based on the DGA method. The ANN approach can produce a high diagnostic accuracy as well as the capability to deal with more complicated problems. However, this powerful diagnostic method requires a large database for training and validation purposes which in turn leads to the problems of overwhelming training time and enormous data storage.

Though considerable efforts in developing such software have been carried out universally over the past few years, much of them are still in their infancy or under development. Most of the software is being sponsored by utility companies for their own in-house usage and none of them is available commercially. Even if such software are available commercially, factors such as different manufacturer's specifications, trends of operations, and local climatic conditions, etc. may make such software unsuitable or may not be directly applicable in some countries. For example, compared to the United Kingdom (U. K.), the climatic conditions in Malaysia are so diverse. The indoor temperature of a substation in Malaysia in the afternoon may be as high as 35^oC whereas in U. K., the temperature in mid-winter may be around 5^oC. In addition to this the humidity factor in Malaysia is around 80% [11, 12] whereas in the U. K. it is much less. Moreover, in Malaysia most of the transformers are operated at around 90 per cent of their capacities, whereas in the United Kingdom, most of the transformers are normally loaded at 50 per cent of their capacities. Due to these factors, TNB embarks on a project with CAIRO UTM to develop expert software for the diagnosis and maintenance of their transformers in the country.

Obviously, transformer maintenance is a time-consuming and costly process. In fact, negligence or delay in transformer fault diagnosis will cause serious disturbance in our life, and worst of all, human lives may be threatened, if a transformer were to explode. Thus, there is a strong urge for developing intelligent fault diagnosis software which is able to interpret diagnostic results more accurately so as to cut cost and ensure better quality service. To achieve the best performance, this intelligent fault diagnosis system must be developed to suit the natural characteristics of local transformers. However, countries with similar environment, transformer usage and other criteria may find this system useful and applicable with minor modification. Hence, this project is motivated by two factors.

- To develop a local intelligent diagnosis system to replace foreign experts so as to save maintenance cost.
- To predict earlier fault that enable precautionary measures to be undertaken so as to minimize the risk of transformer explosion.

1.4 Tenaga National Berhad (TNB) Power Distribution and Maintenance

Tenaga Nasional Berhad (TNB) is the largest electricity utility in Malaysia [1] with more than RM39 billion in assets and serving over 4.5 million customers throughout the Peninsular. The company’s core activities are in the transmission and distribution of electricity. TNB remains a major player in electricity generation which forms a significant part among the company’s diversified range of business activities. To date, through its owned subsidiary, TNB Generation Sdn Bhd, it has the largest generation capacity over 8,100 MW [1], accounting for more than 66 per cent of the total power generation Peninsular Malaysia.

1.4.1 TNB Power Transmission and Distribution Network in Malaysia

TNB's major power plants are strategically located throughout Peninsular Malaysia. The capacity of the utility is generated by conventional thermal, gas turbine, combined cycle and hydro plants [1]. The detail location of the power plants can be found in Figure 1.6. The powers generated from the power plant are then transmitted and distributed to the industry, business center and residential areas. In Peninsular Malaysia, the power transmission and distribution networks can be divided into 9 regions which are listed below [1]:

- Butterworth
- Tanah Merah
- Ipoh
- Kuala Lumpur
- Petalling Jaya
- Melaka
- Kluang
- Johor
- Kuantan

In these 9 regions, there are 12 power stations (Thermal and Hydro) [1] that continuously supply and distribute the electricity to the community everyday and the number of power station is expanding due to the high demand of electricity power in use in the community daily operation. This phenomenon is becoming more significant especially for today’s trend where the Malaysian government emphasized on developing the Multimedia Super Corridor (MSC) project which requires more electricity power consumption. Figure 1.7 shows the power stations and the national grid. As power transformer is a major component in the power station, the more power stations being built will directly affecting the quantity of power transformer in Malaysian. Presently there are about 1000 power transformers operating daily in order to supply the power to the industry and residential area. Appendix A shows the list of power transformer mnemonics in Malaysia.

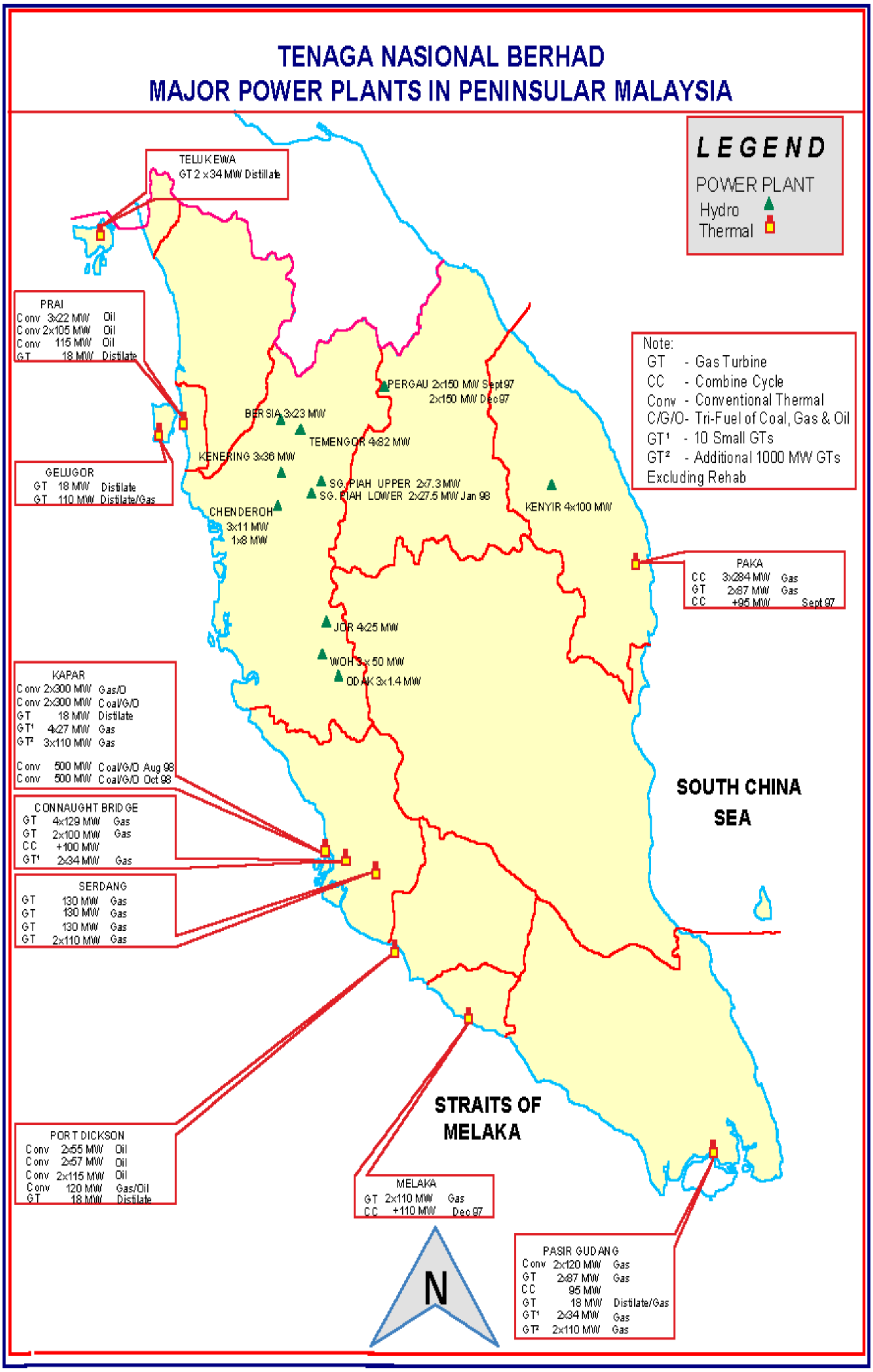


Figure 1.6 : Tenaga Nasional Berhad distribution of major power plants in Peninsular Malaysia in terms of capacities

Figure 1.7: The National Grid

1.4.2 Transformers' Manufacturers

The power transformers in TNB can be categorized into 3 classes according to their voltage which are 132kV, 275kV and 400kV. Among the 3 classes, the 132kV type is most commonly use in TNB [1]. All of these transformers in service in TNB are imported from oversea and manufactured by different foreign manufacturers as shown in Table 1.4.

Table 1.4: Transformer manufacturers

Transformer Manufacturers		
ABB	Ferranti	Rade Kancar
AEG	Fuji	Savigliano
BBC	Heavy Electric	Shen Yang
Bharat	Hyosung	Takaoka
Daihen	Hyundai	Xran
Electro Putere	Meidensha	
Elta	Mitsubishi	
Eracec	Osaka	

1.4.3 Transformers Price

The prices of power transformers mainly depend on the capacity and the manufacturer. On average, the cost for the transformers based on its capacity can be shown in Table 1.5.

Table 1.5: Transformer cost

Capacity (MVA)	Price (RM)
0.3	35,000 – 70,000
7.5	370,000
15	510,000
30	710,000
45	900,000
90	> 1,000,000

1.4.4 Transformer Maintenance and Cost

In order to avoid any interruption of electricity supply due to the faulty transformers, the maintenance job is important to ensure the smooth operation of power transmission and distribution. There are 2 types of maintenance job to be carried out by the TNB engineer which are daily maintenance and periodic maintenance which can be described as follows [13]:

- Daily maintenance

  This maintenance is carried out during transformer operation through regular visual checking. The maintenance jobs include reading and recording the transformer indicators, measuring temperature, checking oil level and leakage, check for the unusual sound or noise and etc.. Details of the daily maintenance guide can be obtained in Appendix B.

- Periodic maintenance

  Periodic maintenance is carried out periodically either in 1, 3 or 6 months time depending on each transformer health condition. During this maintenance, the TNB engineer will inspect more detail on the power transformer which includes DGA analysis on insulating oil, measurement of acid and dielectric strength, bushing test, etc. Details of periodic maintenance guide can be obtained in Appendix B.

Table 1.6: Transformer maintenance cost

Maintenance Type	Cost per transformer (RM)
Dissolved Gas Analysis	350.00
Moisture	45.00
Acidity	40.00
Oil reclamation	5000-10000

The estimated maintenance costs are listed in Table 1.6 [14]. TNB needed to spend about RM 435,000 (RM 435 X 1000 transformers) per month just for the transformer oil testing. This figure not included the cost for locating the experts to interpret the test result. This is needed as power transformers are highly expensive and a catastrophic failure of a transformer is associated with more considerable costs. In the case of catastrophic failure, the event is sudden and no action for a planned outage can be taken. Hence the consequential cost such as loss in produced energy, process down time and penalties may be totally dominating if no redundancy is available. The repair cost normally become more expensive in view that more work need to be carried out for replacing the entire winding set on all phases, rather than just repairing a lead or one winding. Due to these factors, TNB is willing to allocate a large amount of money on maintenance expenses in order to ensure that all the transformers in service are in healthy condition.

1.5 Objectives

This project consists of two main objectives which are listed as follows:

i. To automate the process of analyzing the oil test result, record retrieving and record keeping of large volume of transformer information.

ii. To develop a robust and reliable intelligent diagnostic method to detect and predict faults in transformer automatically.

This proposed intelligent system would be applied to the local industries especially to the power utility company, TNB so as to avoid over dependent on foreign expertise. In order to fulfill the objective, database system management software will developed using Visual Basic 6.0 and Microsoft SQL Server 2000 we call it **A** Software for Intelligent **Dia**gnostic of **P**ower **T**ransformer (ADAPT). This database software can be used to store all the transformer information and the test results, and can also generate different type of useful reports and graphs. In addition, the database software also has a multi-user access feature within a local area network so that users from different location can share and access the record from the database. This, in turn will increase the effectiveness of data retrieval and manipulation.

The second objective is to develop a robust and reliable intelligent diagnostic method to diagnose the fault of the transformer. In order to achieve this objective, four most widely used DGA methods have been integrated to form Total Intelligent Diagnostic Solution (TIDS) architecture so that a more reliable interpretation can be obtained. Besides, all the DGA diagnostic methods in TIDS are incorporated with fuzzy logic algorithm. This is needed as in a fault detection process; it is rather hard to exactly determine the relationship between the phenomena and the reasons for the transformer faults. The faults often show some form of vagueness or fuzziness. Due to this difficulty, fuzzy set theory can be utilized to deal with these uncertainties. Figure 1.8 visualizes the difference between the previous fault diagnostic system and ADAPT.

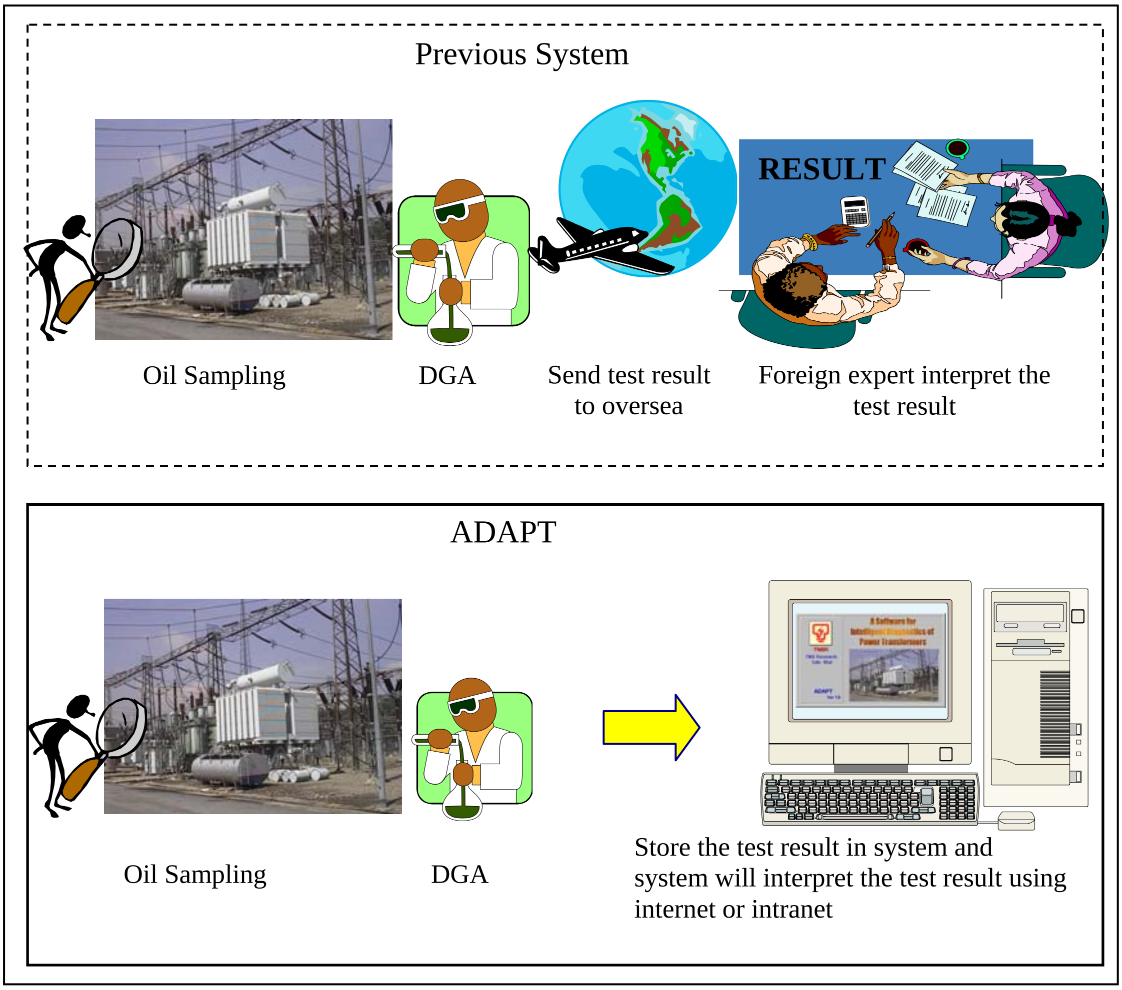


Figure 1.8a: Comparison of conventional fault diagnostic system and ADAPT

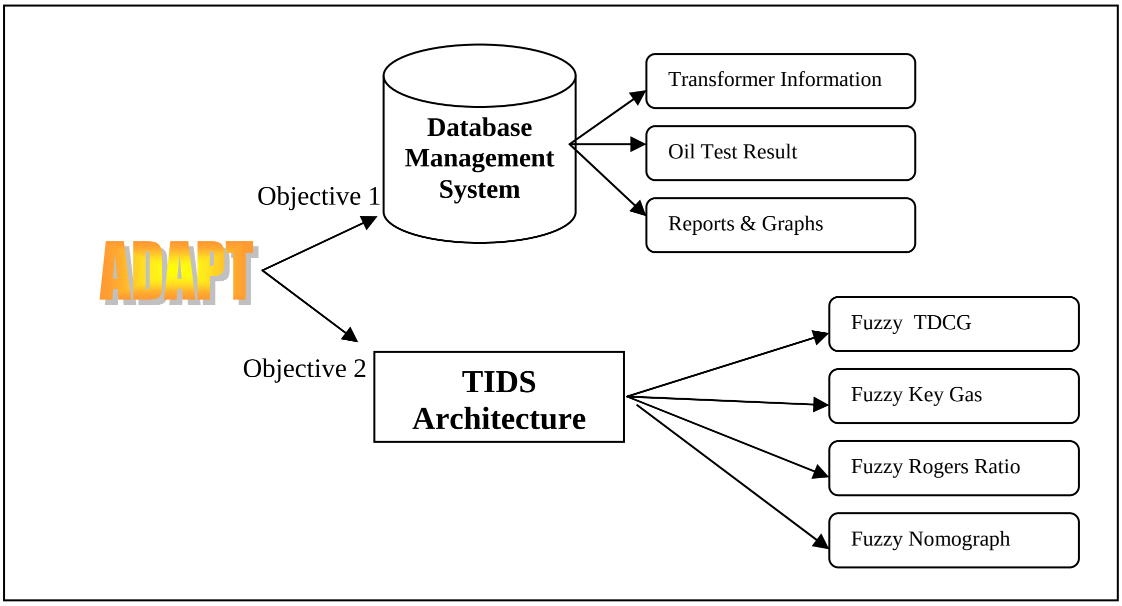


Figure 1.8b: The ADAPT architecture

1.6 Conclusion

This chapter presents an overview of the project. The problem definition, project objectives, project scope, and motivation research are defined and stated clearly. It also gives an overview of the remaining chapters highlighting on the literature review, system design, data and implementation, data analysis, problem encountered, system strengths.

DEDICATION

To Professor Marzuki Khalid, Professor Rubiyah Yusof, En. Shukri Zainal Abidin, Muhammad Afifi bin Abdul Razak, Siti Hajar Aisyah bin Ismail, Muhamad Shakhir bin Jaafar and all people involve in this project.

LIST OF FIGURES

LIST OF TABLES

CHAPTER III

METHODOLOGY

Methodology refers to the branch of philosophy that analyzes the principles and procedures of assumption in a particular discipline. For the purpose of this research, fuzzy logic technique had been used in developing fuzzy fault diagnostic system for power transformers. Fuzzy logic had been applied in various fields such as control system, decision support, fault diagnostics, image processing and data analysis. The fuzzy logic theory was applied in solving nonlinear control problems heuristically and modularly along linguistic lines. The advantages of fuzzy logic are that it exhibits the nature of human thinking and makes decision or judgment using linguistic interpretation. Furthermore, the control rules, regulations and methods based on the perception, experience and suggestion of a human expert were encoded in the meaningful way to avoid mathematical modeling problems.

In this chapter, the concept of fuzzy logic theory, methodology of fuzzy control and decision support systems will be presented. Followed by, the application of the fuzzy logic technique in four DGA faults diagnostic methods namely Fuzzy Rogers Ratio, Fuzzy Key Gas, Fuzzy TDCG and Fuzzy Nomograph and the design methodology of the fuzzy diagnostic system for each of the DGA methods.

3.1 Introduction to Fuzzy Logic

Fuzzy logic is a Boolean logic that has been extended to handle the concept of partial truth which is truth-values between “completely true” and “completely false”. Precisely, it is a multi-valued logic that allows intermediate value to be defined between conventional evaluations like yes/no, true/false and black/white. A fuzzy set allows for the degree of membership of an item in a set to be any real number between 0 and 1. The most powerful aspect of fuzzy set is the ability to deal with linguistic quantifiers or “hedges” (dense). The examples of hedges are “more or less”, “very”, “not very” and “slightly”. This allows human observations, expressions and expertise to be closely modeled. Since then, fuzzy logic had been established as a useful alternative approach for reasoning with imprecision and uncertainty.

3.1.1 Fuzzy Logic Applications

Fuzzy logic has been used in solving of problem domains. These include process control, pattern recognition and classification, management and decision making, operations research and economics. Fuzzy logic is capable in handling non-linear, ill defined, time-varying and complex problem. Fuzzy logic acts as a profitable tool for controlling of subway systems and complex industrial processes, as well as for household, entertainment electronics and diagnostic systems.

Other applications that are using fuzzy logic theory are information retrieval system, decision support systems, data analysis, fault diagnostic systems, voice and handwritten language recognition systems and expert system. Table 3.1 shows a few sample applications of fuzzy logic in real world industry.

Table 3.1: Example of Fuzzy logic applications

Fuzzy Application	**Companies / Organizations**
Single button control for **washing machine**	Matsushita, Hitachi
Pattern Recognition and Medical Imaging	Texas A&M University http://www.cs.tamu.edu
Camera aiming for the telecast of sporting events	Omron
Expert System Shell : FuzzyClips	National Research Council of Canada http://www.nrc.ca
Back light control for **camcorder**	Sanyo
Preventing unwanted temperature fluctuations in **air-conditioning systems**	Mitsubishi, Sharp
FuzzyJava Toolkit and FuzzyJess	National Research Council of Canada's Institute for Information

	Technology http://www.iit.nrc.ca
Substitution for an expert for the **assessment of stock exchange activities**	Yamaichi, Hitachi
Efficient and stable control of **car engines**	Nissan
FCLUSTER - A tool for **fuzzy cluster analysis**	Institute of Knowledge Processing and Language Engineering, University of Magdeburg, Germany http://fuzzy.cs.uni-magdeburg.de
Optimized planning of **bus time-tables**	Toshiba, Nippon-system, Keihan-Express
Improved efficiency and optimized function of **industrial control applications**	Aptronix, Omron, Meiden, Sha, Micom, Mitsubishi, Nisshin-Denki
Automatic motor-control for **vacuum cleaners** with recognition of surface condition and degree of soiling	Mitsubishi
Temperature Control using fuzzy logic	SGH – Thomson Microelectronics
Prediction system for early recognition of earthquakes	Institute of Seismology Bureau of Metrology, Japan
Medicine technology : Cancer diagnosis	Kawasaki Medical School
Fuzzy Logic Controller : Intelligent Control	Xiera Technologies Inc. http://www.xiera.com
Intelligent Agent : Voice recognition	France Telecom www.francetelecom.com
Intelligent Fault Diagnosis of Power Transformers	CAIRO, University of Technology Malaysia

Generally, the application of the fuzzy logic technique is appropriate:

- for very complex processes, when there is no simple mathematical model
- for highly nonlinear processes
- if the processing of (linguistically formulated) expert knowledge is to be performed

3.1.2 The Advantages of Fuzzy Logic

Fuzzy logic technology has emerged as a viable approach in control engineering as well as decision support system. It offers many advantages, which distinctly made it favorable to solve many problems. Below are the four significant advantages:

1) *Solution to nonlinear problems*

   Fuzzy logic is the answer for the problem regarding the unsolved non-linear and complex problems. Fuzzy logic allows heuristic decision-making strategies to be formulated by natural language rules rather than mathematical models. Thus, complex information can be represented by simplified rules.

2) *Ability to handle linguistic variables*

   In many applications, linguistic labels are used to provide meaningful interpretations of the problems. For example, in decision support systems or fault diagnostic systems, knowledge or experiences of the experts is required to be coded into machines. By using fuzzy logic, the expertise or knowledge are extracted from the experts, which is of non-crisp nature can be easily modeled. Fuzzy decision system is more reliable due to the absence of human emotional problems such as bias, boredom and annoyance.

3) *Rule reduction in fuzzy rule base*

   In a conventional expert system, a huge number of rules are needed to describe the input-output relation. The number of rules can be expressed as m^n, where n denotes the number of the system variables and m denotes the number of predicates in the antecedent part of each rule. The large number of rules will degrade the system performance in terms of processing speed and storage. However, the number of rules in a fuzzy logic rule base can be greatly reduced without degrading the performance. A 10:1 rule reduction can be expected in a fuzzy rule base as compared to a conventional rule base [22].

3.1.3 The Disadvantages of Fuzzy Logic

Fuzzy logic technology has been proven to be more effective in solving various kinds of complex or imprecise problems. However, there are some limitations of fuzzy logic, which are unavoidable. There can be summarized as follows:

1) *Highly dependent on domain expert's knowledge*

The use of the fuzzy logic technique concept is to translate the expert knowledge into a collection of machine understandable rules. Unlike other artificial intelligent techniques, such as neural networks and genetic algorithms, problem is solved via training process. A well-defined knowledge base is needed in fuzzy logic to solve any kind of problems. Hence, the knowledge extraction process is crucial as the whole fuzzy system is dependent on the domain expert knowledge. If the domain experts provide wrong information, then the system may not be functioning well as required. Thus, it is important to acquire correct knowledge for the correct experts.

2) *Lack of information*

Fuzzy control can be applied in many processes if there is enough information or relevant knowledge about the process and its control strategies. Solving a totally unknown or impossible job that even human experts cannot accomplish is rather difficult to be accomplished using fuzzy logic technique.

3) *Insufficient design standard or methodology*

Fuzzy logic has been applied in various applications by number of researchers around the world. However, most of the researchers use their own ways to design their applications. They usually use heuristic or trial and error approach in selecting the types of membership functions, inference engine and defuzzification methods. This approach is time-consuming as the number of the fuzzy partitions and mapping of the membership functions are the important factors that might affect the performance of the result. Thus, a standard fuzzy system design guideline or systematic design methodology is needed in order to obtain satisfactory results for fuzzy systems and reduce the development time constraints.

3.2 Fuzzy Logic Control System

Fuzzy logic control system mainly consists of four major elements, which are a fuzzification unit, a fuzzy inference engine, fuzzy knowledge base and a defuzzification unit. The typical structure for the fuzzy logic control system is shown in Figure 3.7. The input values are normally in the crisp value, thus, the fuzzification and defuzzification operations are needed to map these values into fuzzy values used internally by the fuzzy logic control system or to defuzzify it into a crisp value. The output from the defuzzification unit can be an action for controlling certain machine or it can be a decision based on the knowledge of the decision-maker in fuzzy decision support system.

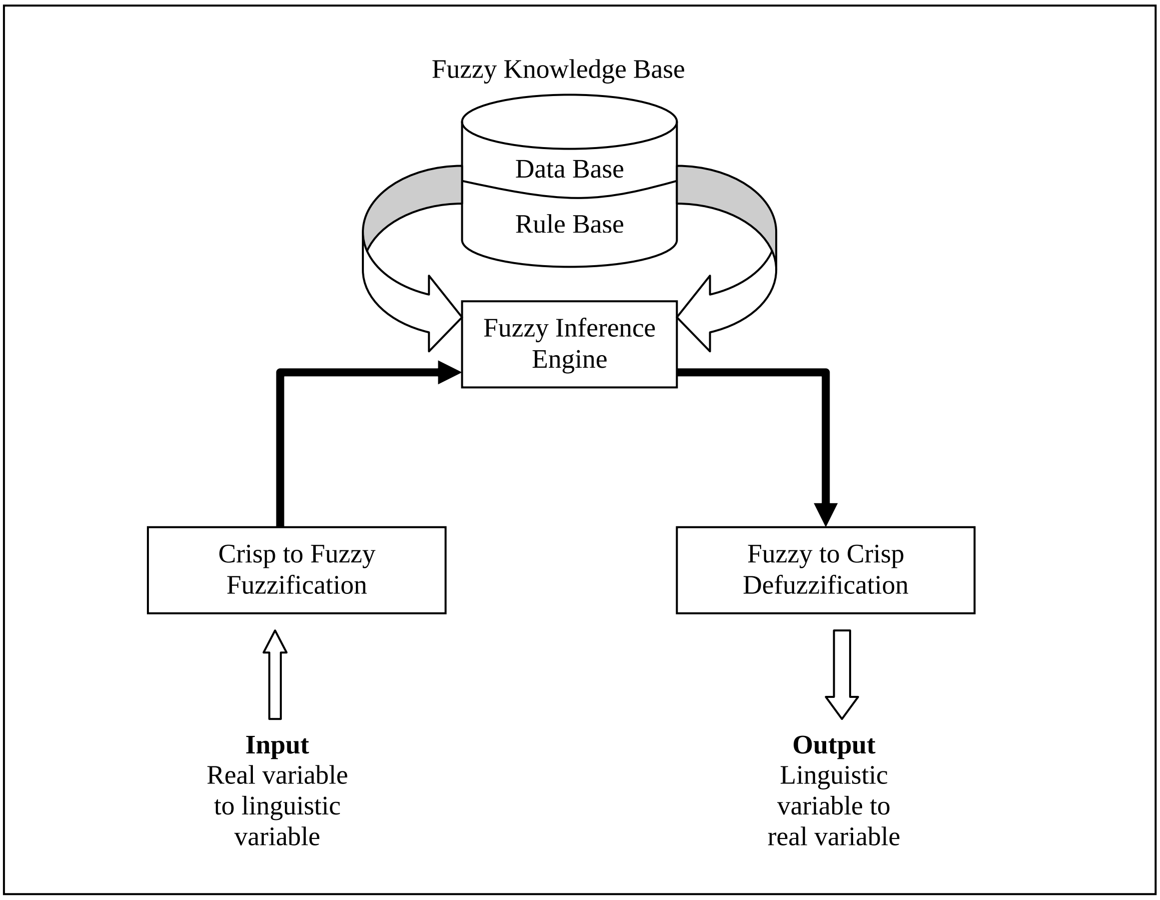


Figure 3.1 : Basic structure of a fuzzy logic control system

3.2.1 Fuzzification

Fuzzification is the process of mapping from observed inputs to fuzzy sets into the various input universes of discourse. In process control, the observed data is usually in crisp set and fuzzification is required to map the observed range of crisp inputs to corresponding fuzzy values for the system input variables. The mapped data are further converted into suitable linguistic terms as labels of the fuzzy set defined for system input variables. When the variable is classified with a membership function, the expected output is the degree of membership. This process of classifying a variable using membership function and degree of membership is called fuzzification. Basically, the linguistic term is an understandable variable. A linguistic variable is characterized by a quintuple (x, T(x), U, M) in which x is the name of the variable, T(x) is the term set of x, that is the set of names of linguistic variable values of x with each value being a fuzzy variable defined on U. M is a semantic rule for associating each value of x with its meaning. For example, if x = Temperature with U=[0,100] degree Celsius, then the term set T(Temperature) may be defined as

T(Temperature) = { Very Cold, Cold, Warm, Hot, Very Hot }

and the semantic M could be defined as

M(Hot) = fuzzy set for "temperature between 80 and 90 degree Celsius" with membership function μ_{hot}.

3.2.2 Fuzzy Knowledge Base

A fuzzy knowledge base usually consists of a group of fuzzy rules, which is extracted from experts. There are no formal standard to follow in constructing the fuzzy rules. In most engineering control application, the fuzzy rules are expressed as "IF-THEN" style. For example, "IF x is A THEN y is B".

The reason is to provide a convenient way to human expert in expressing their knowledge and experience. Furthermore, it also provides the designers with an easy way to construct and to program the fuzzy rules.

The knowledge base consists of a database and a rule base. The database defines fuzzy parameter as fuzzy sets with membership function that defined for each variable.

Construction of the database involves defining the universe of discourse for each variable, determining the number of fuzzy sets and designing the membership function. For industrial applications, analog is the most values that been measured.
The analog values are converted to digital to be input to a digital computer system.
The process is called quantization in which it separates the measurement into segments. A fuzzy set is now defined by assigning degree of membership value to each generic element of the new discrete universe.

The rule base consists of a collection of fuzzy control rules based on the control objective and control policy. The fuzzy control rules are able to infer a properly control action for any input in the universe of discourse. This property is referred as “completeness”. The property of completeness is included into fuzzy control rules through design experience and engineering knowledge. It involves overlapping fuzzy sets to ensure that every value is matched by some fuzzy set. Then the rules are carefully design to ensure that every input generates some response. An additional rule might need to be added, if the degree of partial match between some inputs and predefined fuzzy conditions is lower than a certain level.

In construction of the fuzzy rules, four principal methods have been employed as described below:

1) *An expert’s experience or control engineering knowledge.*
   Most of the fuzzy logic controller designs are based on the expertise and experience of domain experts. This is because fuzzy control rules provide a natural framework for capturing expert knowledge. It provides a convenient way for the experts to express their domain knowledge. Designing fuzzy control rule bases by interrogating experts and trying to capture their approach in fuzzy rules are done in an interactive way. The fuzzy parameters of the initial system that obtain from the experts are often being tuned and adjusted until the satisfactory performance is achieved.

2) *Modeling the operator’s control actions.*
   In many control system, skilled worker can control the complex system successfully without having any quantitative model in mind. Therefore, it is possible to derive fuzzy control rules by modeling the skilled operator’s control actions. Designing fuzzy control rules in this way is a deterministic approach. In practice, modeling the operator’s control actions is carried out by observing the human controller’s action

or behavior over a period of time and expressing them in terms of the operational input-output data.

3) *A fuzzy model of the process.*

Fuzzy modeling is a qualitative modeling scheme in which the behavior of the system to be controlled is qualitatively described using fuzzy linguistic. This linguistic description of the dynamic characteristics of the controlled process may be viewed as a fuzzy model of the process. Based on the fuzzy model, we can generate a set of fuzzy control rules to obtain optimal performance of the system.

4) *Learning.*

Fuzzy logic system can be built to dynamically generate rules or adjust rules automatically, which is quite similar to human learning process. Currently, many research efforts are focused on constructing a highly intelligence and adaptive systems using neural networks, self-tuning and self-organizing, which can simulate the human learning behavior.

3.2.3 Fuzzy Inference Engine

There are various types in which the observed input values can be used to identify the most appropriate rules. The most well known types are Mamdani's Max-Min implication method and Larsen's Max-Product implication method.

Based on the Mamdani Max-Min inference method and for a set of disjunctive rules, the aggregated output for the n rules will be given by

$$\mu_{C_k}(Z) = MaxMin_k\left\lfloor \mu_{A_k}(input(i)), \mu_{B_k}(input(j)) \right\rfloor \tag{3.7}$$

Figure 3.8 show the Max-Min inference process for the crisp input i and j. This figure illustrates the graphical analysis of two rules where the symbols A_1 and B_1 refer to the first and the second fuzzy antecedents of the first rule while the symbol Z_1 refers to the fuzzy consequent of the first rule. Symbols A_2, B_2 and Z_2 refer to the antecedents and consequent for the second rule. The minimum function in Equation 3.7 is illustrated in Figure 3.8 and arises because the antecedent pair given in the general rule structure for this system are connected by a logical "AND" connective. The minimum membership value for the antecedents propagates through to the consequent and truncates the membership function for the consequent of each rule. This graphical inference is done for each rule. Then the truncated membership functions for each rule are aggregated. The aggregation operation max results in an aggregated membership form from each rule. Then, the real value z* for the aggregated output can be obtained through the defuzzification technique.

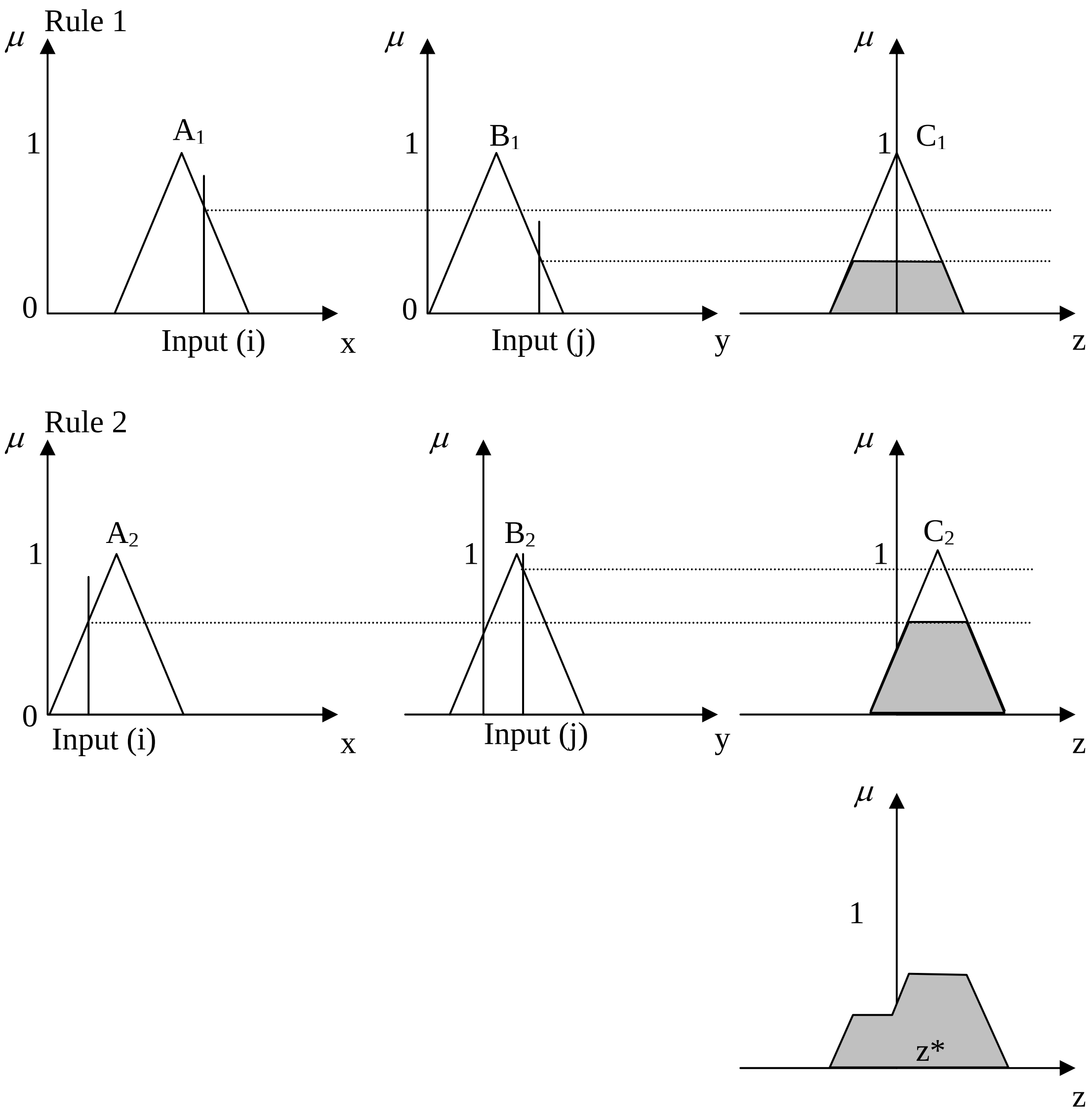


Figure 3.2 : Max-Min inference process

In Max-Dot fuzzy reasoning technique, for a set of disjunctive rules, the aggregated output for the n-th rule would be given by

$$\mu_{C_k}(Z) = Max\left\lfloor \mu_{A_k}(input(i)) \bullet \mu_{B_k}(input(j)) \right\rfloor \qquad (3.8)$$

Figure 3.9 shows the Max-Dot inference process for the crisp input i and j. The effect of the Max-Dot implication is shown by the consequent membership functions as scaled triangles. This figure also shows the aggregated consequent resulting from a disjunctive set if rules and a defuzzified value z*, resulting from the defuzzification method.

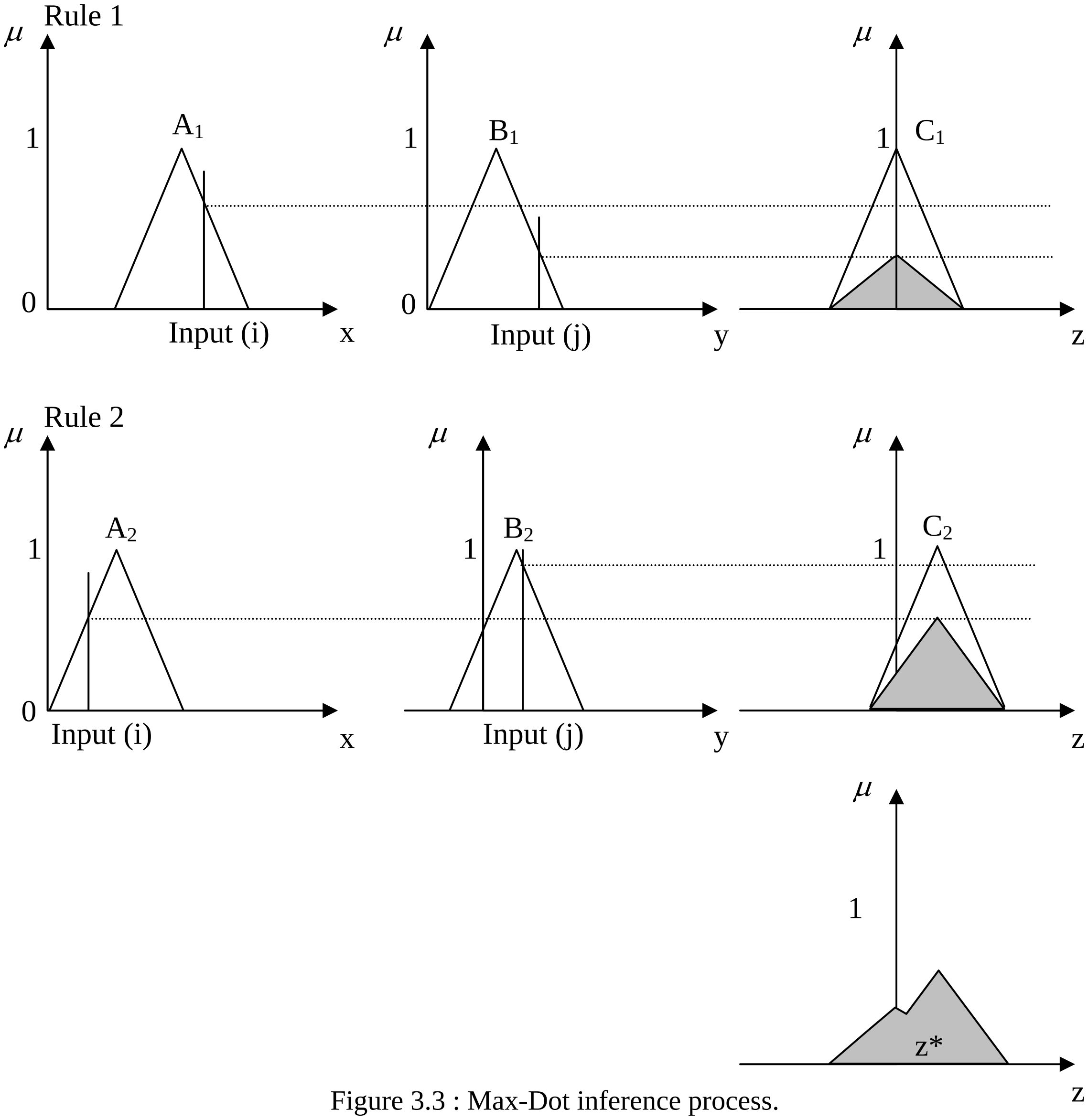


Figure 3.3 : Max-Dot inference process.

3.2.4 Defuzzification

Defuzzification is used to convert the fuzzy linguistic variable to real variable. It is the process of mapping from a space of inferred fuzzy control actions to a space of non-fuzzy (crisp) control actions. A defuzzification strategy is aimed at producing a non-fuzzy control action that best represents the possibility distribution of the inferred fuzzy control action. There are a number of defuzification methods and the most commonly used defuzzification methods are described as follows:

i) Max-membership defuzzification

Maximum-membership defuzification scheme where the element that has the maximal membership is chosen such that:

$$\mu_c(z^*) \geq \mu_c(z) \qquad \text{for all } z \in Z \qquad (3.9)$$

where $\mu_c(z^*)$ is the peaked output function in the universe of discourse Z as shown graphically in Figure 3.10.

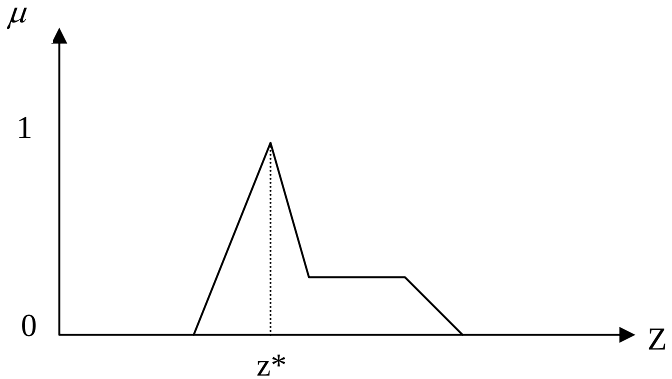


Figure 3.4 : Max membership defuzzification method

ii) Center of Gravity or Centroid

In this method, the crisp value of the output variable is computed by finding the variable value of the center of gravity of the membership function for the fuzzy value as shown in Figure 3.11. This method is given by equation:

$$z^* = \frac{\sum \mu_C(z) \cdot z}{\sum \mu_C(z)} \qquad \text{for all } z \in Z \qquad (3.10)$$

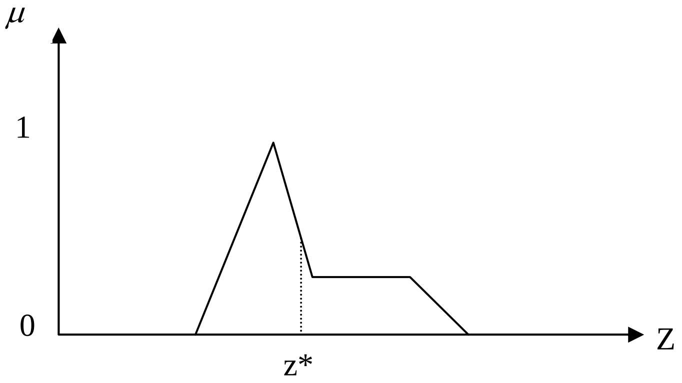


Figure 3.5: Centroid defuzzification method

iii) Mean-max membership method

This method is similar to the Max-membership method and only applicable when there are more than one maximum membership functions as shown in Figure 3.13. This method is given by the expression:

$$z^* = \frac{a+b}{2} \qquad \text{for all } z \in Z \tag{3.11}$$

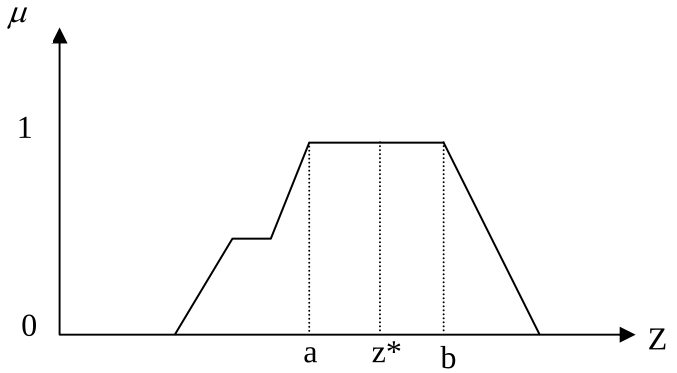


Figure 3.6: Mean-Max membership defuzzification method

3.3 Introduction to Fuzzy Diagnostic System

In the fault detection process, it is hard to determine the relationship between the phenomena and the reasons for the transformer faults. The faults often show some form of vagueness or fuzziness. For example, according to the Key Gas standard, high concentration of gas Acetylene (C_2H_2) is related to the fault of Arcing and the gas C_2H_2 concentration of 35 ppm is considered normal. However, sometimes at 35 ppm, the transformer may indicate Arcing condition. Due to this difficulty, fuzzy set theory can be utilized to deal with these uncertainties. Through fuzzy set theory, the membership grade function can translate uncertain or qualitative information into quantitative data. Fuzzy logic is known for its capability in handling linguistic variables. Linguistic labels are used to provide meaningful interpretations of the problems at hand. Thus, fuzzy logic is popular in many applications; including problems of complex system diagnosis.

3.4 The Design Methodology of Fuzzy Diagnostic System

To implement a reliable and robust fuzzy diagnostic system, there is a general procedure in designing a fuzzy system. This procedure is shown in Figure 3.13. The detail of this procedure is as described below [24]:

1. Identification of the fuzzy input and output variables

   Before applying fuzzy logic, it is important to understand the whole system process and the objective of applying it. Then, a fuzzy system is designed by determining the fuzzy input and output variables that are required to construct the fuzzy logic system.

2. Quantization

   This step is to determine the number of fuzzy partitions of the input-output linguistic variables. Each of the fuzzy variables needs to be quantified into smaller subsets appropriately. The process must be conducted carefully because the number of fuzzy partitions may affect the performance of the control system. However, the more partitions do not necessary mean better control performance. An optimum number of partitions will make the system more efficient.

3. Assignment of membership functions

   The usages of membership functions are based on the system variable. Thus, the appropriate membership functions are needed for the input and output fuzzy variables. The most commonly used membership functions are the Triangular, L-function, Γ-function and Trapezoidal.

4. Fuzzy inference rule base setup

   The rule base consists of a collection of fuzzy control rules based on the control objective and control policy. In constructing the fuzzy rules, the four principle methods that have been discussed in Section 3.22 can be used.

5. Selection of fuzzy compositional operator (inference engine)

   There are various ways in which the observed input values can be used to identify the most appropriate rules to infer a suitable fuzzy control action. However, the Mamdani’s Max-Min method is the most commonly used method and is used in this project.

6. Selection of defuzzification procedure

   Defuzzification is used to convert the fuzzy linguistic variable to variable. For fuzzy diagnostic system or decision support system, Max-membership defuzzification method is chosen where the element that has the maximum membership is chosen.

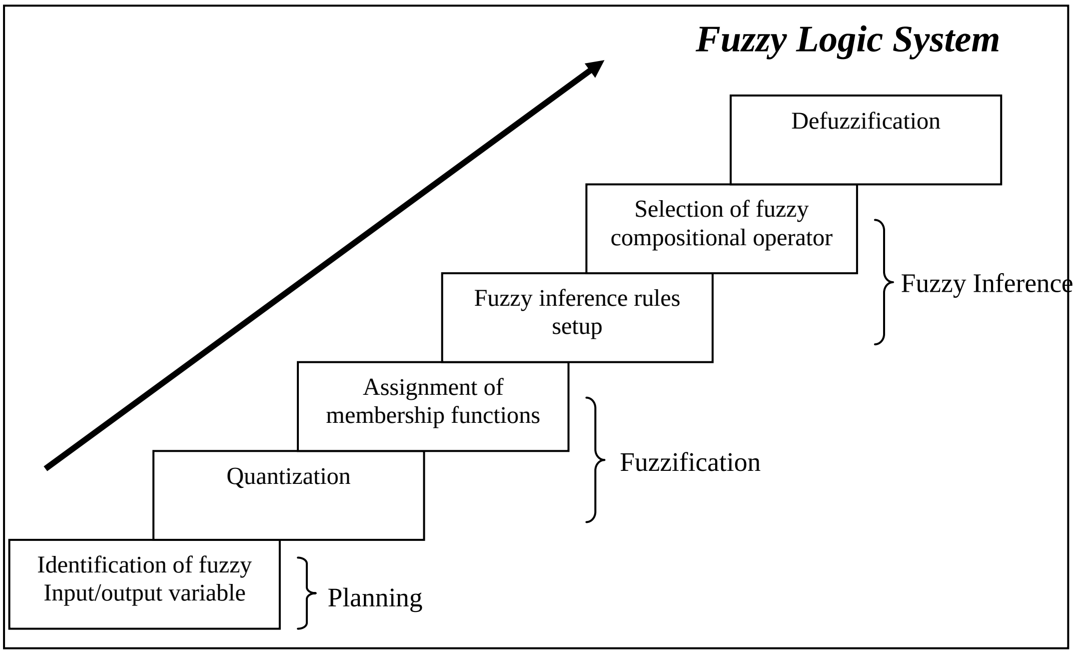


Figure 3.7 : Steps for constructing a fuzzy logic system

3.5 Fuzzy Rogers Ratio

The 4-gas ratio range introduced by Ron Rogers, known as "Rogers Ratio", may not exactly provide the accurate range in reality. In practice, factors such as the loading history, transformer construction, oil volume, manufacturer and the weather condition may affect the ratio range as well. All these factors may affect the diagnostic of the transformer. As a result, a significant number of the DGA results may fall out of the listed codes of diagnostic conditions. In addition, the crisp sets used to classify the codes are not sufficient to handle the boundary conditions of the gas ratios especially when the values are closed to the threshold values of 0.1, 1.0 or 3.0. As a result, the classification for the codes of the gas ratio becomes contentious and less accurate diagnosis may occur. These restrictions entail the development of the Fuzzy Rogers Ratio diagnostic systems.

3.5.1 Identification of Fuzzy Input and Output Variable for Fuzzy Rogers Ratio Method

Rogers Ratio method uses the 4-digit ratio code generated from the 5 fault gases which are Acetylene, Ethylene, Methane, Hydrogen and Ethane to determine 15 transformer conditions. Therefore, the structure for the Fuzzy Rogers Ratio system can be illustrated in Figure 3.14 where the four ratio codes are identified as the input parameter while the 15 interpretation results based on the difference combination of ratio code are identified as the output parameter.

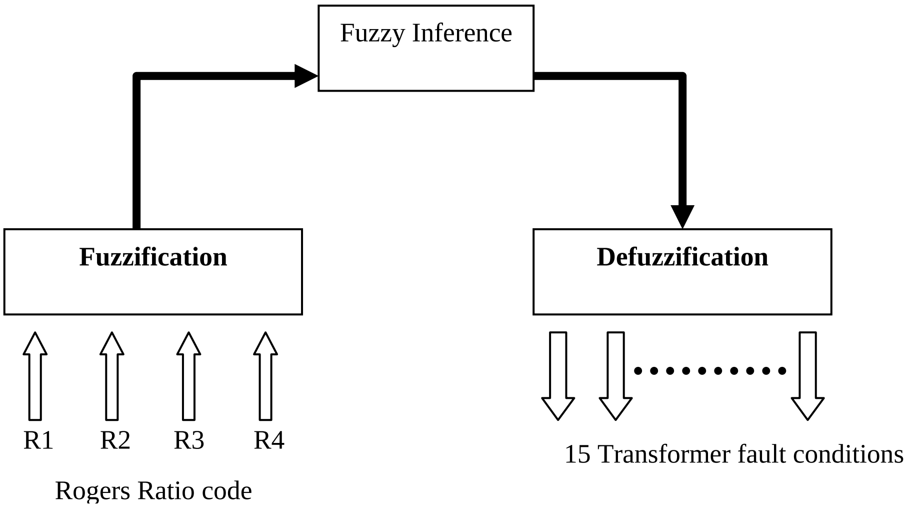


Figure 3.8 : Input and output variables for the Fuzzy Rogers Ratio method

The input parameter and output parameter in Figure 3.14 can be summarized as follows:

Input

Ratio 1 = Acetylene / Ethylene (AE)

Ratio 2 = Methane / Hydrogen (MH)

Ratio 3 = Ethylene / Ethane (EE)

Ratio 4 = Ethane / Methane (EM)

Output

A : No fault: normal deterioration

B : Partial discharges of low energy density or hydrolysis

C : Partial discharges of high energy density, possibly with tracking

D : Coincidental partial discharges and conductor overheating

E : Partial discharges of increasing energy density

F : Low energy discharge: flashover without power follow through

G : Low energy discharge: continuous sparking to floating potential

H : High energy discharge: arc with power follow through

I : Insulated conductor overheating

J : Complex thermal hotspot and conductor overheating

K : Coincidental thermal hotspot and low energy discharge

M : Thermal fault of low temperature range < 150^{0}C

N : Thermal fault of temperature range 100 - 200^{0}C

O : Thermal fault of temperature range temperature range 150 - 300^{0}C overheating of copper due to eddy currents

P : Thermal fault of high temperature range 300 - 700^{0}C: bad contacts/ joints (pyrolytic carbon formation): core and tank circulating currents

3.5.2 Quantization

The approach used in fuzzifying the gas ratios according to the method of Roger's Ratio will be discussed in this section. The real variables are converted into the appropriate linguistic variables. The 4 ratios are classified as Low (Lo), Medium (Med), High (Hi) and Very High (Vhi) term set according to their membership intervals as defined below:

AE = {Lo, Med, Hi}
MH = {Lo, Med, Hi, Vhi}
EE = {Lo, Med, Hi}
EM = {Lo, Hi}

Table 3.2, 3.3, 3.4 and 3.5 shows the number of linguistic term being used for the fuzzy Rogers Ratio.

Table 3.2: Term set for C_2H_2/C_2H_4 ratio

AE =C_2H_2/C_2H_4	
	Ratio Range
Lo	AE < 0.1
Med	$0.1 \le AE \le 3.0$
Hi	AE > 3.0

Table 3.3: Term set for CH_4/H_2 ratio

MH =CH_4/H_2	
	Ratio Range
Lo	MH < 0.1
Med	$0.1 \le MH \le 1.0$
Hi	$1.0 < MH \le 3.0$
VHi	MH > 3.0

Table 3.4: Term set for C_2H_4/C_2H_6 ratio

EE =C_2H_4/C_2H_6	
	Ratio Range
Lo	EE < 1.0
Med	$1.0 \le EE \le 3.0$
Hi	EE > 3.0

Table 3.5: Term set for C_2H_6/CH_4 ratio

EM =C_2H_6/CH_4	
	Ratio Range
Lo	EM < 1.0
Hi	$EM \ge 3.0$

$$AE = C_2H_2 / C_2H_4 = \begin{cases} 0 & Lo & U < 0.1 \\ 1 & Med & 0.1 \le U \le 3.0 \\ 2 & Hi & U > 3.0 \end{cases} \tag{3.12}$$

$$MH = CH_4 / H_2 = \begin{cases} 5 & Lo & U < 0.1 \\ 0 & Med & 0.1 \leq U \leq 1.0 \\ 1 & Hi & 1.0 \leq U \leq 3.0 \\ 2 & Vhi & U > 3.0 \end{cases} \tag{3.13}$$

$$EE = C_2H_4 / C_2H_6 = \begin{cases} 0 & Lo & U < 1.0 \\ 1 & Med & 1.0 \leq U \leq 3.0 \\ 2 & Hi & U > 3.0 \end{cases} \tag{3.14}$$

$$EM = C_2H_6 / CH_4 = \begin{cases} 0 & Lo & U < 1.0 \\ 1 & Hi & U \geq 1.0 \end{cases} \tag{3.15}$$

3.5.3 Assignment of Membership Functions

This approach is using the membership functions of type Triangular, Trapezoidal, L-function and Γ-function. The fuzzy membership function for the Roger 4 ratio input classifications are given in Figure 3.15, 3.16, 3.17 and 3.18 for Acetylene / Ethane (AE), Methane / Hydrogen (MH), Ethane / Ethylene (EE) and Ethane / Methane (EM) respectively.

AE $\in$ { Lo, Med, Hi }

Based on Table 3.2, ratio AE is low when $C_2H_2/ C_2H_4 < 0.1$. The AELo membership is going to the value of one for small u and zero for large u. Thus, L-function is being used for classifying AELo.

$$\text{AELo (u; a, b)} = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \leq u \leq b \\ 0 & u > b \end{cases} \tag{3.16}$$

Based on Table 3.2, ratio AE is medium when $0.1 \le C_2H_2/\ C_2H_4 \le 3.0$. The AEMed membership is going to the value of one when $0.1 \le u \le 3.0$ and zero for both large and small u. Thus, Trapezoid-function is being used for classifying AEMed

$$\text{AEMed }(u; a, b, c, d) = \begin{cases} 0 & u < a \\ \dfrac{u-a}{b-a} & a \le u < b \\ 1 & b \le u \le c \\ \dfrac{d-u}{d-c} & c < u \le d \\ 0 & u > d \end{cases} \qquad (3.17)$$

Based on Table 3.2, ratio AE is high when $C_2H_2/\ C_2H_4 > 3.0$. The AEHi membership is going to the value of one for large u and zero for small u. Thus, Γ-function is being used for classifying AEHi

$$\text{AEHi }(u; c, d) = \begin{cases} 1 & u > d \\ \dfrac{u-c}{d-c} & c \le u \le d \\ 0 & u < c \end{cases} \qquad (3.18)$$

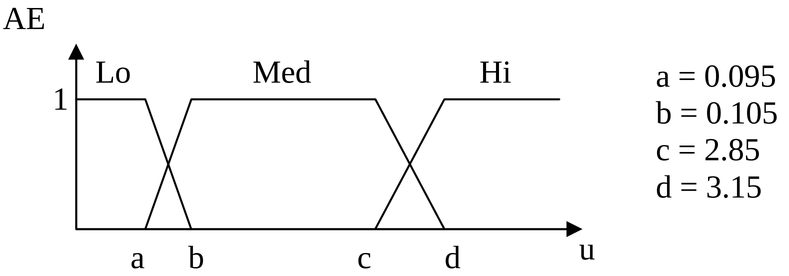


Figure 3.9 : Fuzzy membership functions used in classifying Acetylene / Ethane ratio for Rogers Ratio Method

MH $\in$ { Lo, Med, Hi, VHi }

Based on Table 3.3, ratio MH is low when $CH_4/H_2 < 0.1$. The MHLo membership is going to the value of one for small u and zero for large u. Thus, L-function is being used for classifying MHLo.

$$\text{MHLo (u; a, b)} = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \le u \le b \\ 0 & u > b \end{cases} \tag{3.19}$$

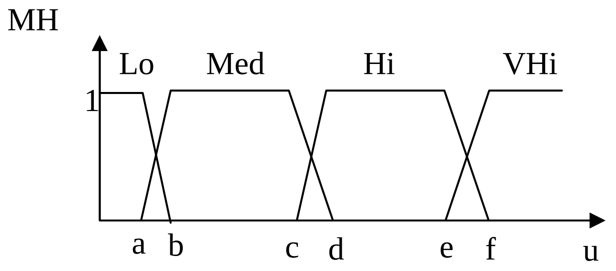
Based on Table 3.3, ratio MH is medium when $0.1 \le CH_4/H_2 \le 1.0$ and MH is high when $1.0 < CH_4/H_2 \le 3.0$. The MHMed and MHHi membership is going to the value of one in the range $0.1 \le u \le 1.0$ and $1.0 < u \le 3.0$. Thus, Trapezoid-function is being used for classifying MHMed and MHHi.

$$\text{MHMed (u; a, b, c, d)} = \begin{cases} 0 & u < a \\ \dfrac{u-a}{b-a} & a \le u < b \\ 1 & b \le u \le c \\ \dfrac{d-u}{d-c} & c < u \le d \\ 0 & u > d \end{cases} \tag{3.20}$$

$$\text{MHHi (u; c, d, e, f)} = \begin{cases} 0 & u < c \\ \dfrac{u-c}{d-c} & c \le u < d \\ 1 & d \le u \le e \\ \dfrac{f-u}{f-e} & e < u \le f \\ 0 & u > f \end{cases} \tag{3.21}$$

Based on Table 3.3, ratio MH is very high when $CH_4/H_2 > 3.0$. The MHVHi membership is going to the value of one for large u and zero for small u. Thus, Γ-function is being used for classifying MHVHi.

$$\text{MHVHi (u; e, f)} = \begin{cases} 1 & u > f \\ \dfrac{u-e}{f-e} & e \le u \le f \\ 0 & u < e \end{cases} \tag{3.22}$$



a = 0.095
b = 0.105
c = 0.95
d = 1.05
e = 2.85
f = 3.15

Figure 3.10 : Fuzzy membership functions used in classifying Methane / Hydrogen ratio for Rogers Ratio Method

EE $\in$ { Lo, Med, Hi }

Based on Table 3.4, ratio EE is low when C_2H_4 / $C_2H_6 < 1.0$. The EELo membership is going to the value of one for small u and zero for large u. Thus, L-function is being used for classifying EELo.

$$\text{EELo}(u; a, b) = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \leq u \leq b \\ 0 & u > b \end{cases} \tag{3.23}$$

Based on Table 3.4, ratio EE is medium when $1.0 \leq C_2H_4 / C_2H_6 \leq 3.0$. The EEMed membership is going to the value of one when $1.0 \leq u \leq 3.0$ and zero for both large and small u. Thus, Trapezoid-function is being used for classifying EEMed.

$$\text{EEMed}(u; a, b, c, d) = \begin{cases} 0 & u < a \\ \dfrac{u-a}{b-a} & a \leq u < b \\ 1 & b \leq u \leq c \\ \dfrac{d-u}{d-c} & c < u \leq d \\ 0 & u > d \end{cases} \tag{3.24}$$

Based on Table 3.4, ratio EE is high when C_2H_4 / C_2H_6 > 3.0. The EEHi membership is going to the value of one for large u and zero for small u. Thus, Γ-function is being used for classifying EEHi.

$$\text{EEHi }(u; c, d) = \begin{cases} 1 & u > d \\ \dfrac{u-c}{d-c} & c \le u \le d \\ 0 & u < c \end{cases} \qquad (3.25)$$

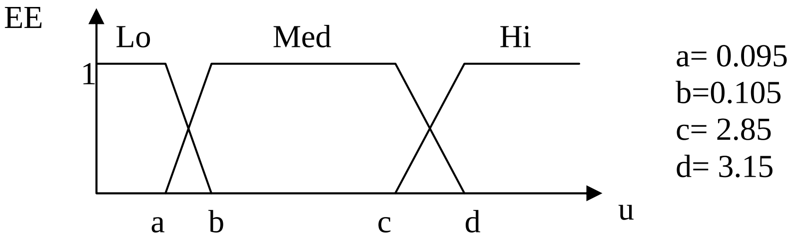


Figure 3.11 : Fuzzy membership functions used in classifying Ethylene / Ethane ratio for Rogers Ratio Method

EM $\in$ { Lo, Hi }

Based on Table 3.5, ratio EM is low when C_2H_6 / CH_4 < 1.0. The EMLo membership is going to the value of one for small u and zero for large u. Thus, L-function is being used for classifying EMLo.

$$\text{EMLo }(u; a, b) = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \le u \le b \\ 0 & u > b \end{cases} \qquad (3.26)$$

Based on Table 3.5, ratio EM is high when C_2H_6 / CH_4 > 3.0. The EMHi membership is going to the value of one for large u and zero for small u. Thus, Γ-function is being used for classifying EMHi.

$$\text{EMHi (u; c, d)} = \begin{cases} 1 & u > b \\ \dfrac{u-a}{b-a} & a \leq u \leq b \\ 0 & u < a \end{cases} \tag{3.27}$$

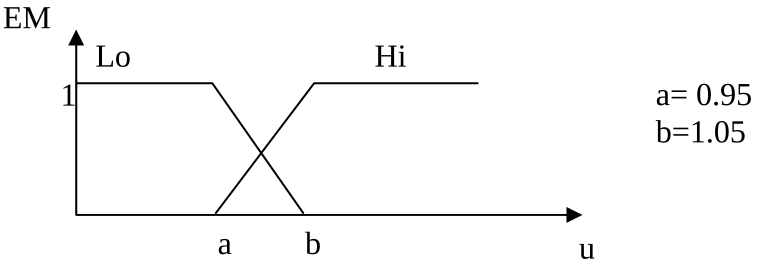


Figure 3.12 : Fuzzy membership functions used in classifying Ethane / Methane ratio for Rogers Ratio Method

3.5.4 Fuzzy Inference Rules Setup

Fuzzy inference rules consist of a collection of rules which are extracted from the expert. Normally, fuzzy inference consists of two components which are antecedent (if part) and consequent (then part). For this application, the fuzzy inference rules can be extracted from the Roger's ratio fault interpretation guide. There are a total of 22 fuzzy inference rules that can be derived from Rogers fault interpretation guide which is summarized in Table 3.6. Due to the limitation of Rogers Ratio method, only 22 fuzzy inferences can be derived out of the total of 72 rules (4x3x3x2). However, with the fuzzy logic techniques which allow partial membership may improve the number of matched cases as compared to the ordinary crisp set theory. All the rules derived from Rogers Ratio methods using fuzzy logic technique are shown in Table 3.7.

Table 3.6 : Classification of the Rogers Ratio codes

		AE=L			AE=M			AE=H		
		EE =L	EE =M	EE =H	EE =L	EE =M	EE =H	EE =L	EE =M	EE =H
MH =L	EM=L	B	D		C					
	EM=H	E								
MH =M	EM=L	A	I		F	G	H	F	G	H
	EM=H	N	J		K					
MH	EM=L	M	O	P	K					

=H	EM=H	N								
MH =VH	EM=L			P						
	EM=H	N								

A : No fault: normal deterioration

B : Partial discharges of low energy density or hydrolysis

C : Partial discharges of high energy density, possibly with tracking

D : Coincidental partial discharges and conductor overheating

E : Partial discharges of increasing energy density

F : Low energy discharge: flashover without power follow through

G : Low energy discharge: continuous sparking to floating potential

H : High energy discharge: arc with power follow through

I : Insulated conductor overheating

J : Complex thermal hotspot and conductor overheating

K : Coincidental thermal hotspot and low energy discharge

M : Thermal fault of low temperature range < 150^0C

N : Thermal fault of temperature range 100 - 200^0C

O : Thermal fault of temperature range temperature range 150 - 300^0C overheating of copper due to eddy currents

P : Thermal fault of high temperature range 300 - 700^0C: bad contacts/ joints (pyrolytic carbon formation): core and tank circulating currents

Table 3.7 : Fuzzy inference rules for Rogers Ratio method

Rule 1	If MH=L and AE=L and EE=L and EM=L then Condition B
Rule 2	If MH=L and AE=L and EE=L and EM=H then Condition E
Rule 3	If MH=L and AE=L and EE=M and EM=L then Condition D
Rule 4	If MH=L and AE=M and EE=L and EM=L then Condition C
Rule 5	If MH=M and AE=L and EE=L and EM=L then Condition A
Rule 6	If MH=M and AE=L and EE=L and EM=H then Condition N
Rule 7	If MH=M and AE=L and EE=M and EM=L then Condition I
Rule 8	If MH=M and AE=L and EE=M and EM=H then Condition J
Rule 9	If MH=M and AE=M and EE=L and EM=L then Condition F
Rule 10	If MH=M and AE=M and EE=L and EM=H then Condition K
Rule 11	If MH=M and AE=M and EE=M and EM=L then Condition G
Rule 12	If MH=M and AE=M and EE=H and EM=L then Condition H
Rule 13	If MH=M and AE=H and EE=L and EM=L then Condition F
Rule 14	If MH=M and AE=H and EE=M and EM=L then Condition G
Rule 15	If MH=M and AE=H and EE=H and EM=L then Condition H
Rule 16	If MH=H and AE=L and EE=L and EM=L then Condition M
Rule 17	If MH=H and AE=L and EE=L and EM=H then Condition N
Rule 18	If MH=H and AE=L and EE=M and EM=L then Condition O

Rule 19	If MH=H and AE=L and EE=H and EM=L then Condition P
Rule 20	If MH=H and AE=M and EE=L and EM=L then Condition K
Rule 21	If MH=VH and AE=L and EE=L and EM=H then Condition N
Rule 22	If MH=VH and AE=L and EE=H and EM=L then Condition P

3.5.5 Selection of Fuzzy Compositional Operator

The output of the fuzzy inference can be obtained using the Mamdani's Max-Min composition technique as shown as follows:

Antecedent:

Rule 1 = Min{MH=L, AE=L,EE=L, EM=L}
Rule 2 = Min{MH=L, AE=L,EE=L, EM=H}
Rule 3 = Min{MH=L, AE=L, EE=M, EM=L}
Rule 4 = Min{MH=L, AE=M, EE=L, EM=L}
Rule 5 = Min{MH=M, AE=L, EE=L, EM=L}
Rule 6 = Min{MH=M, AE=L, EE=L, EM=H}
Rule 7 = Min{MH=M, AE=L, EE=M, EM=L}
Rule 8 = Min{MH=M, AE=L, EE=M, EM=H}
Rule 9 = Min{MH=M, AE=M, EE=L, EM=L}
Rule 10 = Min{MH=M, AE=M, EE=L, EM=H}
Rule 11 = Min{MH=M, AE=M, EE=M, EM=L}
Rule 12 = Min{MH=M, AE=M, EE=H, EM=L}
Rule 13 = Min{MH=M, AE=H, EE=L, EM=L}
Rule 14 = Min{MH=M, AE=H, EE=M, EM=L}
Rule 15 = Min{MH=M, AE=H, EE=H, EM=L}
Rule 16 = Min{MH=H, AE=L, EE=L, EM=L}
Rule 17 = Min{MH=H, AE=L, EE=L, EM=H}
Rule 18 = Min{MH=H, AE=L, EE=M, EM=L}
Rule 19 = Min{MH=H, AE=L, EE=H, EM=L}
Rule 20 = Min{MH=H, AE=M, EE=L, EM=L}
Rule 21 = Min{MH=VH, AE=L, EE=L, EM=H}
Rule 22 = Min{MH=VH, AE=L, EE=H, EM=L}

The consequent are computed as follows:

Condition A = Max {rule 5}
Condition B = Max {rule 1}
Condition C = Max {rule 4}
Condition D = Max {rule 3}
Condition E = Max {rule 2}
Condition F = Max {rule 9, rule 13}
Condition G = Max {rule 11, rule 14}
Condition H = Max {rule 12, rule 15}
Condition I = Max {rule 7}
Condition J = Max {rule 8}
Condition K = Max {rule 10, rule 20}
Condition M = Max {rule 16}
Condition N = Max {rule 6, rule 17, rule 21}
Condition O = Max {rule 18}
Condition P = Max {rule 19, rule 22}

Example:

Assume that the degrees of membership function of the Rogers 4 ratio are listed below:

MHH=0 MHM =1 AEM=1 EEL=0.785 EMH=0.9 EML=0.1

Rule 10 = Min {MH=M, AE=M, EE=L, EM=H}
= Min {1, 1, 0.785, 0.9} = 0.785

Rule 20 = Min {MH=H, AE=M, EE=L, EM=L}
= Min {0, 1, 0.785, 0.1} = 0

Condition K = Max {rule 10, rule 20}
= Max {0.785, 0}
= 0.785

3.5.6 Defuzzification

For fuzzy diagnostic system, the suitable defuzzification method is Max-membership defuzzification where the output is chosen from the element that has the maximum degree of membership function. After selecting the maximum membership function, the severity of certain condition can be classified based on the degree of membership function as defined in Table 3.8.

Table 3.8: Degree of membership function

Degree of membership	Severity
1	Absolutely Yes
0.75 – 0.99	Most Probably
0.50 – 0.74	Probably
0.25 – 0.49	Little Chance
0.01– 0.24	Slim Chance
0	Absolutely No

Example:
Assume that condition K is the maximum membership function:
Condition K to the degree of 0.785

Interpretation:
The transformer is ***most probably*** in coincidental thermal hotspot and low energy discharge.

3.5.7 Fuzzy Rogers Ratio Diagnosis

This section demonstrates how the Fuzzy Rogers Ratio fault diagnosis works. For this demonstration, a real test result provided by TNBR Sdn. Bhd. is being evaluated by using the Fuzzy Rogers Ratio method. The test result is taken from a transformer KULS T2A at the Kuala Lumpur region with rated voltage of 132/33 kV. The test results are listed as follows:

Hydrogen (H_2) = 324 ppm
Acetylene (C_2H_2) = 575 ppm
Ethylene (C_2H_4) = 185 ppm
Ethane (C_2H_6) = 15 ppm
Methane (CH_4) = 98 ppm

1. Identifying fuzzy Input variable for Fuzzy Rogers Ratio:

Ratio 1 = Acetylene / Ethylene (AE) = 3.108
Ratio 2 = Methane / Hydrogen (MH) = 0.302
Ratio 3 = Ethylene / Ethane (EE) = 12.333
Ratio 4 = Ethane / Methane (EM) = 0.153

2. Fuzzification:
Ratio 1:
AELo = 0.000
AEMed = 0.860
AEHi = 0.140

Ratio 2:
MHLo = 0.000
MHMed = 1.000
MHHi = 0.000
MHVhi = 0.000

Ratio 3:
EELo = 0.000
EEMed = 0.000
EEHi = 1.000

Ratio 4:
EMLo = 1.000
EMHi = 0.000
3. Fuzzy inference:

Aggregation

Rule 1 = Min{MH=L, AE=L,EE=L, EM=L} = 0.000
Rule 2 = Min{MH=L, AE=L,EE=L, EM=H} = 0.000
Rule 3 = Min{MH=L, AE=L, EE=M, EM=L} = 0.000
Rule 4 = Min{MH=L, AE=M, EE=L, EM=L} = 0.000
Rule 5 = Min{MH=M, AE=L, EE=L, EM=L} = 0.000
Rule 6 = Min{MH=M, AE=L, EE=L, EM=H} = 0.000
Rule 7 = Min{MH=M, AE=L, EE=M, EM=L} = 0.000
Rule 8 = Min{MH=M, AE=L, EE=M, EM=H} = 0.000
Rule 9 = Min{MH=M, AE=M, EE=L, EM=L} = 0.000
Rule 10 = Min{MH=M, AE=M, EE=L, EM=H} = 0.000
Rule 11 = Min{MH=M, AE=M, EE=M, EM=L} = 0.140
Rule 12 = Min{MH=M, AE=M, EE=H, EM=L} = 0.140
Rule 13 = Min{MH=M, AE=H, EE=L, EM=L} = 0.000
Rule 14 = Min{MH=M, AE=H, EE=M, EM=L} = 0.000
Rule 15 = Min{MH=M, AE=H, EE=H, EM=L} = 0.860
Rule 16 = Min{MH=H, AE=L, EE=L, EM=L} = 0.000
Rule 17 = Min{MH=H, AE=L, EE=L, EM=H} = 0.000
Rule 18 = Min{MH=H, AE=L, EE=M, EM=L} = 0.000
Rule 19 = Min{MH=H, AE=L, EE=H, EM=L} = 0.000
Rule 20 = Min{MH=H, AE=M, EE=L, EM=L} = 0.000
Rule 21 = Min{MH=VH, AE=L, EE=L, EM=H} = 0.000
Rule 22 = Min{MH=VH, AE=L, EE=H, EM=L} = 0.000

Composition

Condition A = Max {rule 5} = 0.000
Condition B = Max {rule 1} = 0.000
Condition C = Max {rule 4} = 0.000
Condition D = Max {rule 3} = 0.000
Condition E = Max {rule 2} = 0.000
Condition F = Max {rule 9, rule 13} = 0.000
Condition G = Max {rule 11, rule 14} = 0.140
Condition H = Max {rule 12, rule 15} = 0.860

Condition I = Max {rule 7} = 0.000
Condition J = Max {rule 8} = 0.000
Condition K = Max {rule 10, rule 20} = 0.000
Condition M = Max {rule 16} = 0.000
Condition N = Max {rule 6, rule 17, rule 21} = 0.000
Condition O = Max {rule 18} = 0.000
Condition P = Max {rule 19, rule 22} = 0.000

4. Composition:
Condition H with degree of membership 0.86 is selected due to its largest degree of membership function.

5. Defuzzification:
The transformer is ***most probably*** in High Energy Discharge: Arc with Power Follow Through.

3.6 Fuzzy Key Gas

A set of rules to diagnose abnormalities such as Thermal, Corona or Arcing problems is employed The Key Gas method. It is a reliable diagnostic method because it can be used to diagnose the condition of the transformer even there are only a few gases obtained from the oil sample. Comparatively, the Rogers Ratio method requires all 5 necessary ratio gases to be detected correctly earlier to produce satisfactory result. However, there is a possibility that the ratio code cannot provide meaningful information due to the absent of certain gases. In this case, Fuzzy Key Gas method which uses the individual gas rather than the calculation gas ratio for detecting fault condition will be a perfect candidate to offset the limitation of the Rogers Ratio method. The key gases and its relation to the type of fault are listed below:

- H_2 – Corona (CN)
- CO & CO_2 – Cellulose insulation breakdown (CIB)
- CH_4 & C_2H_6 – Low temperature oil breakdown (LTOB)
- C_2H_4 – High temperature oil breakdown (HTOB)
- C_2H_2 – Arcing (ARC)

3.6.1 Identification of Fuzzy Input and Output Variable for Fuzzy Key Gas method

The first step of applying the Fuzzy Key Gas method is to determine the input and output variables by examining the relation of the key gases with the fault type. For this case, 7 input parameter can be used to determine 5 outputs which can be summarized as in Figure 3.19 below:

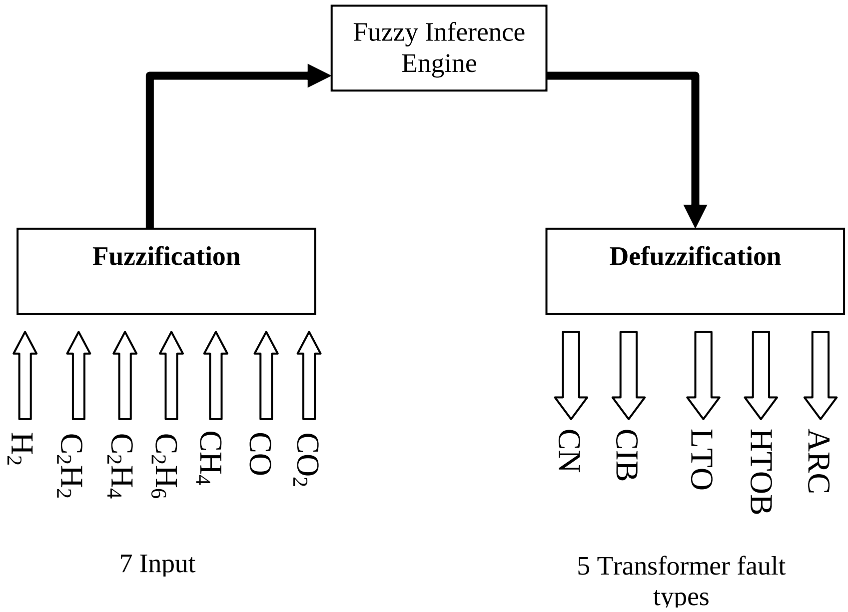


Figure 3.13: Input and output variables for Fuzzy Key Gas method

3.6.2 Quantization

The quantization step is to define the threshold values for all the 7 input gases. The international recognized standard can be used to define the threshold value for Key Gas method. Based on the IEEE Standard, 7 input variables have been classified into Low (Lo), Medium (Med) and High (Hi) term set. From the 3 term sets, the IEEE standard value is being used as the medium term set while the high and low term set are being adjusted 5 percent more or 5 percent less than the medium term set respectively as defined in Table 3.9.

Table 3.9: Key Gas threshold value

	High	Medium	Low
H_2	105	100	95
C_2H_2	36.75	35	33.25
C_2H_4	52.5	50	47.5
C_2H_6	68.25	65	61.75
CH_4	126	120	114
CO	367.5	350	332.5
CO_2	2625	2500	2375

3.6.3 Assignment of Membership Functions

For the Fuzzy Key Gas fault diagnostic method, the appropriate types of membership function are Triangular, L-function and Γ-function. The fuzzy membership function for the Key Gas input classifications are given in Figure 3.20, 3.21, 3.22, 3.23, 3.24, 3.25 and 3.26 for H_2, CO, CO_2, C_2H_2, C_2H_4, C_2H_6 and CH_4 respectively.

L-function is applicable for all key gases with ***low*** term set due to the membership going to one for small u and zero for large u.

$$\text{KeyGasLo (u; a, b)} = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \le u \le b \\ 0 & u > b \end{cases} \qquad (3.28)$$

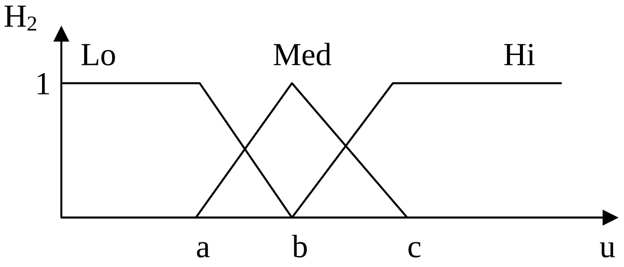
Triangular-function is applicable for all key gases with ***medium*** term set due to the membership going to one in a narrow range of u value and zero for both large and small u.

$$\text{KeyGasMed(u; a, b, c)} = \begin{cases} 0 & for \quad u < a \\ (u-a)/(b-a) & for \quad a \leq u \leq b \\ (c-u)/(c-b) & for \quad b \leq u \leq c \\ 0 & for \quad u > c \end{cases} \tag{3.29}$$

Γ-function is applicable for all key gases with ***high*** term set due to the membership going to one for large u and zero for small u.

$$\text{KeyGasHi (u; b, c)} = \begin{cases} 1 & u > c \\ \dfrac{u-b}{c-b} & b \leq u \leq c \\ 0 & u < b \end{cases} \tag{3.30}$$

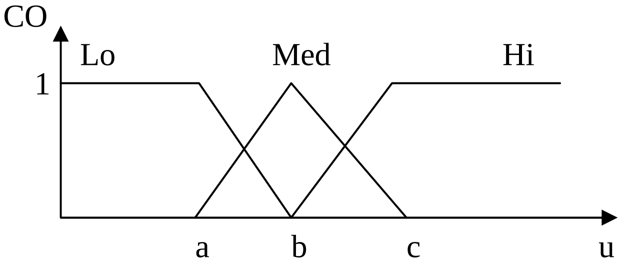
H_2 $\in$ { Lo, Med, Hi }



a = 105
b = 100
c = 95

Figure 3.14 : Fuzzy membership functions used in classifying Hydrogen

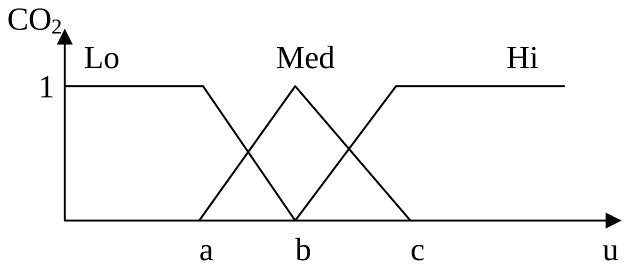
CO $\in$ { Lo, Med, Hi }



a = 367.5
b = 350
c = 332.5

Figure 3.15 : Fuzzy membership functions used in classifying Carbon Monoxide

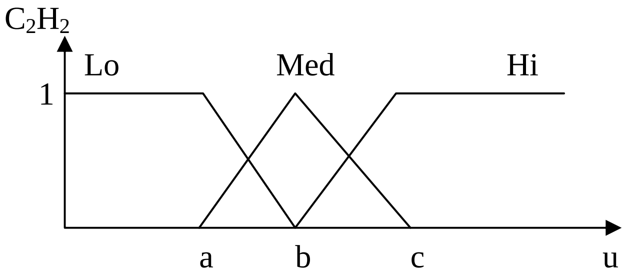
CO_2 ∈ { Lo, Med, Hi }



a = 2625
b = 2500
c = 2375

Figure 3.16 : Fuzzy membership functions used in classifying Carbon Dioxide

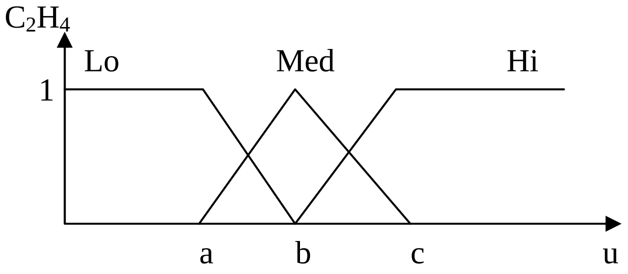
C_2H_2 ∈ { Lo, Med, Hi }



a = 36.75
b = 35
c = 33.25

Figure 3.17 : Fuzzy membership functions used in classifying Acetylene

C_2H_4 ∈ { Lo, Med, Hi }



a = 52.5
b = 50
c = 47.5

Figure 3.18 : Fuzzy membership functions used in classifying Ethylene

C_2H_6 ∈ { Lo, Med, Hi }

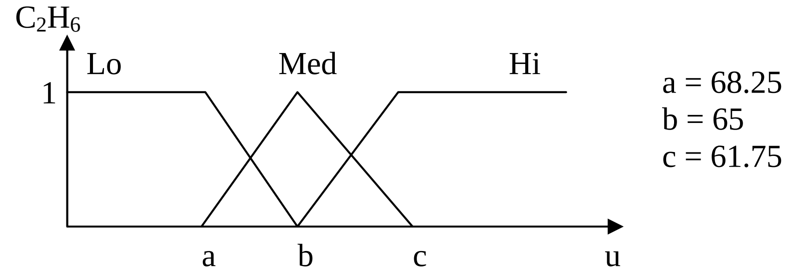


Figure 3.19 : Fuzzy membership functions used in classifying Ethane

$CH_4 \in \{$ Lo, Med, Hi $\}$

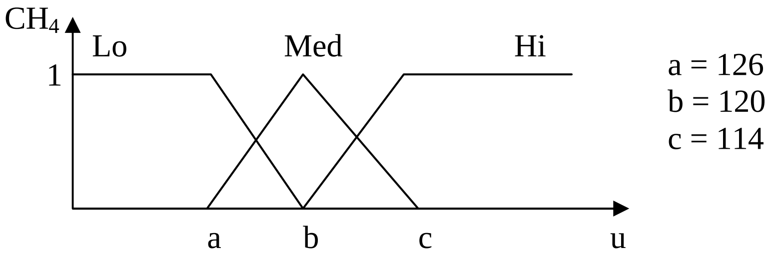


Figure 3.20 : Fuzzy membership functions used in classifying Methane

3.6.4 Fuzzy Inference Rules Setup

In the Fuzzy Key Gas diagnostic method, there are a total of 27 fuzzy inference rules can be derived from the Key Gas that related to fault type based on the IEEE Standard [5] guide which are listed in Table 3.10.

Table 3.10 : Fuzzy inference rules for Fuzzy Key Gas method

Rule 1	If H_2=Hi then CN=Y
Rule 2	If H_2=Med then CN=N
Rule 3	If H_2=Lo then CN=N
Rule 4	If CO=Hi and CO_2=Hi then CIB=Y
Rule 5	If CO=Hi and CO_2=Med then CIB=Y
Rule 6	If CO=Hi and CO_2=Lo then CIB=N
Rule 7	If CO=Med and CO_2=Hi then CIB=Y
Rule 8	If CO=Med and CO_2=Med then CIB=N
Rule 9	If CO=Med and CO_2=Lo then CIB=N
Rule 10	If CO=Lo and CO_2=Hi then CIB=Y
Rule 11	If CO=Lo and CO_2=Med then CIB=N
Rule 12	If CO=Lo and CO_2=Lo then CIB=N
Rule 13	If C_2H_2=Hi then ARC=Y
Rule 14	If C_2H_2=Med then ARC=N

Rule 15	If C_2H_2=Lo then ARC=N
Rule 16	If C_2H_4=Hi then HTOB=Y
Rule 17	If C_2H_4=Med then HTOB=N
Rule 18	If C_2H_4=Lo then HTOB=N
Rule 19	If CH_4=Hi and C_2H_6=Hi then LTOB=Y
Rule 20	If CH_4=Hi and C_2H_6=Med then LTOB=Y
Rule 21	If CH_4=Hi and C_2H_6=Lo then LTOB=Y
Rule 22	If CH_4=Med and C_2H_6=Hi then LTOB=Y
Rule 23	If CH_4=Med and C_2H_6=Med then LTOB=N
Rule 24	If CH_4=Med and C_2H_6=Lo then LTOB=N
Rule 25	If CH_4=Lo and C_2H_6 =Hi then LTOB=Y
Rule 26	If CH_4=Lo and C_2H_6=Med then LTOB=N
Rule 27	If CH_4=Lo and C_2H_6=Lo then LTOB=N

CN = Corona
CIB = Cellulose Insulation Breakdown
ARC = Arcing
HTOB = High Temperature Oil Breakdown
LTOB = Low Temperature Oil Breakdown
Y = Yes
N = No

3.6.5 Selection of Fuzzy Compositional Operator

The output of the fuzzy inference can be obtained using the Mamdani's Max-Min composition technique is shown as follows:

Antecedent:

Rule 1 = Min{ H_2=Hi }
Rule 2 = Min{ H_2=Med }
Rule 3 = Min{ H_2=Lo }
Rule 4 = Min{ CO=Hi and CO_2=Hi }
Rule 5 = Min{ CO=Hi and CO_2=Med }
Rule 6 = Min{ CO=Hi and CO_2=Lo }
Rule 7 = Min{ CO=Med and CO_2=Hi }
Rule 8 = Min{ CO=Med and CO_2=Med }
Rule 9 = Min{ CO=Med and CO_2=Lo }
Rule 10 = Min{ CO=Lo and CO_2=Hi }
Rule 11 = Min{ CO=Lo and CO_2=Med }

Rule 12 = Min{ CO=Lo and CO_2=Lo }
Rule 13 = Min{ C_2H_2=Hi }
Rule 14 = Min{ C_2H_2=Med }
Rule 15 = Min{ C_2H_2=Lo }
Rule 16 = Min{ C_2H_4=Hi }
Rule 17 = Min{ C_2H_4=Med }
Rule 18 = Min{ C_2H_4=Lo }
Rule 19 = Min{ CH_4=Hi and C_2H_6=Hi }
Rule 20 = Min{ CH_4=Hi and C_2H_6=Med }
Rule 21 = Min{ CH_4=Hi and C_2H_6=Lo }
Rule 22 = Min{ CH_4=Med and C_2H_6=Hi }
Rule 23 = Min{ CH_4=Med and C_2H_6=Med }
Rule 24 = Min{ CH_4=Med and C_2H_6=Lo }
Rule 25 = Min{ CH_4=Lo and C_2H_6 =Hi }
Rule 26 = Min{ CH_4=Lo and C_2H_6=Med }
Rule 27 = Min{ CH_4=Lo and C_2H_6=Lo }

The consequent are computed as follows:

CN = Max {Rule 1}
CIB = Max {Rule 4, Rule 5, Rule 7, Rule 10}
LTOB = Max {Rule 19, Rule 20, Rule 21, Rule 22, Rule 25}
HTOB = Max {Rule 16}
ARC = Max {Rule 13}

3.6.6 Defuzzification

As discussed above, a suitable defuzzification method for fuzzy diagnosis system is the Max-membership defuzzification method where the element that has the maximum degree of membership function is chosen. For Fuzzy Key Gas, 3 conditions are determined for all the 5-fault types which are ***critical***, ***cautious*** and ***normal***. The critical condition means that the transformer has the specific fault type and immediate action must be taken to solve the problem. For cautious condition, the transformer may have the specific fault and hence should be monitored more frequently and normal condition is only for the healthy transformer. These 3 conditions are categorized according to the degree of membership function which may indicates the severity of each fault type as shown in Table 3.11.

Table 3.11 : Degree of membership function

Degree of membership	Condition
0.8-1	Critical
0.5-0.79	Cautious
0-0.49	Normal

An example of a fuzzy interpretation can be as follows:
The transformer is in ***Critical*** *condition of Cellulose Insulation Breakdown.*

3.7 Fuzzy TDCG

Total Dissolved Combustible Gas (TDCG) in transformer fault detection concept is useful in finding out the suitable oil-sampling interval based on the health condition of the transformer so as to compensate the conflict between excessive cost due to over sampling and neglected danger owing to long sampling period. In general, TDCG uses the sum of the 6 key gas values and the TDCG gas generation rate to determine the operating procedure and predict suitable oil sampling interval as shown in Table 3.12.

Table 3.12 : Action based on TDCG

Status / TDCG	TDCG Rates (ppm/day)	Sampling Intervals and Operating Procedures for Gas Generation Rates	
		Sampling Interval	Operating Procedure
Condition 1 < 720	> 30	Monthly	Exercise caution. Analyse for individual gases. Determine load dependence.
	10 – 30	Quarterly	Continue normal operation.
	< 10	6 Month	
Condition 2 721 – 1920	> 30	Monthly	Exercise caution. Analyse for individual gases. Determine load dependence.
	10 – 30		
	< 10	Quarterly	
Condition 3 1921 – 4630	> 30	Weekly	Exercise caution. Analyse for individual gases. Plan outage.
	10 – 30		
	< 10	Monthly	

Condition 4 > 4630	> 30	Daily	Consider removal from service.
	10 – 30		
	< 10	Weekly	Exercise caution. Analyse for individual gases. Plan outage.

Although the TDCG method is widely used in solving fault diagnosis problem, but in the certain cases, it is very hard to determine the correct group of the TDCG value especially when the TDCG value falls near the boundary line as shown in the TDCG rules set in Table 3.12. The fuzzy logic technique is advantages in solving this problem.

3.7.1 Identification Fuzzy Input and Output Variable for Fuzzy TDCG Method

For the TDCG diagnostic method, the sum of the 6 fault gases and the gas generation rate are required to determine the health condition of a power transformer. Thus, for Fuzzy TDCG method, the fuzzy inputs are TDCG value and the TDCG gas generation rate while the sampling interval and the operation procedure are the fuzzy output variable. The structure for the Fuzzy TDCG method can be illustrated in Figure 3.27 and the TDCG value and TDCG gas generation rate can be calculated by Equation 3.31 and 3.32 respectively.

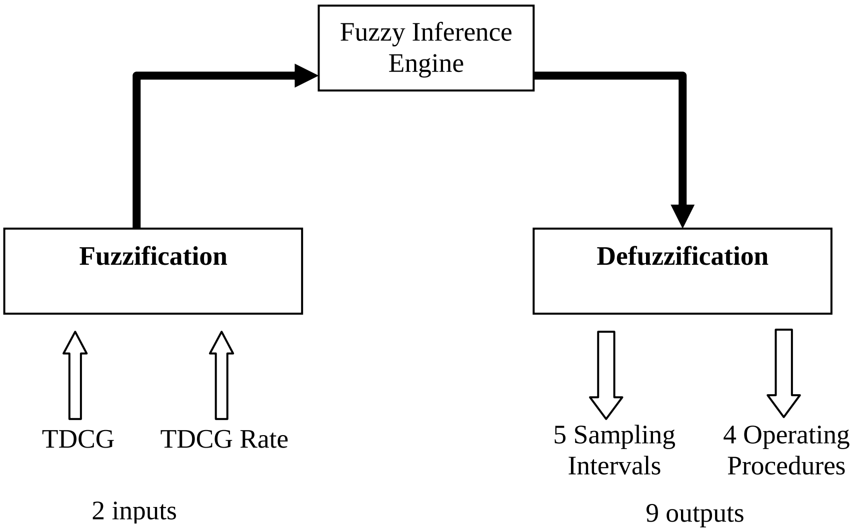


Figure 3.21 : Input and output variables in the Fuzzy TDCG method

$$TDCG = C_2H_2 + C_2H_4 + H_2 + CH_4 + C_2H_6 + CO \qquad (3.31)$$

$$TDCG\ Rate = \frac{(St - So)}{T} \qquad (3.32)$$

Where St = Current TDCG So = Previous TDCG
T = Time in days

3.7.2 Quantization

Based on the crisp set rules in Table 3.12, the TDCG and TDCG rate value can be classified as Low, Medium, High and Very High according to membership interval as defined below:

TDCG = { Lo, Med, Hi, Vhi }
TDCG_Rate = { Lo, Med, Hi }

$$\text{TDCG} = \begin{cases} Lo & U < 720 \\ Med & 721 \le U \le 1920 \\ Hi & 1921 \le U \le 4630 \\ Vhi & U > 4630 \end{cases} \qquad (3.33)$$

$$\text{TDCG\_Rate} = \begin{cases} Lo & U < 10 \\ Med & 10 \le U \le 30 \\ Hi & U > 30 \end{cases} \qquad (3.34)$$

3.7.3 Assignment of Membership Functions

The membership functions of type Trapezoidal, L-function and Γ-function are used in this approach. The fuzzy membership function for the Fuzzy TDCG input classifications are given in Figure 3.28 and 3.29 for TDCG and TDCG_Rate respectively.

TDCG $\in$ { Lo, Med, Hi, Vhi }

L-function is being used for TDCGLo due to the membership going to the value of one for small u and zero for large u.

$$\text{TDCGLo (u; a, b)} = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \le u \le b \\ 0 & u > b \end{cases} \tag{3.35}$$

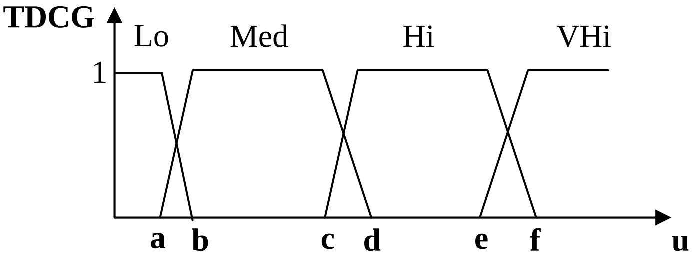
Trapezoid-function is being used for TDCGMed and TDCGHi due to the membership going to the value of one when b ≤ u ≤ c and zero for both large and small u.

$$\text{TDCGMed (u; a, b, c, d)} = \begin{cases} 0 & u < a \\ \dfrac{u-a}{b-a} & a \le u < b \\ 1 & b \le u \le c \\ \dfrac{d-u}{d-c} & c < u \le d \\ 0 & u > d \end{cases} \tag{3.36}$$

$$\text{TDCGHi (u; c, d, e, f)} = \begin{cases} 0 & u < c \\ \dfrac{u-c}{d-c} & c \le u < d \\ 1 & d \le u \le e \\ \dfrac{f-u}{f-e} & e < u \le f \\ 0 & u > f \end{cases} \tag{3.37}$$

Γ-function is being used for TDCGVhi due to the membership going to the value of one for large u and zero for small u.

$$\text{TDCGVhi (u; e, f)} = \begin{cases} 1 & u > f \\ \dfrac{u-e}{f-e} & e \le u \le f \\ 0 & u < e \end{cases} \tag{3.38}$$



a = 715
b = 725
c = 1915
d = 1925
e = 4625
f = 4635

Figure 3.22 : Fuzzy membership functions used in classifying the TDCG value

TDCG_Rate $\in$ { Lo, Med, Hi,}

L-function is being used for TDCG_RateLo due to the membership going to the value of one for small u and zero for large u.

$$\text{TDCG\_RateLo (u; a, b)} = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \le u \le b \\ 0 & u > b \end{cases} \qquad (3.39)$$

Trapezoid-function is being used for TDCG_RateMed due to the membership going to the value of one when b ≤ u ≤ c and zero for both large and small u.

$$\text{TDCG\_RateMed (u; a, b, c, d)} = \begin{cases} 0 & u < a \\ \dfrac{u-a}{b-a} & a \le u < b \\ 1 & b \le u \le c \\ \dfrac{d-u}{d-c} & c < u \le d \\ 0 & u > d \end{cases} \qquad (3.40)$$

Γ -function is being used for TDCG_RateHi due to the membership going to the value of one for large u and zero for small u.

$$\text{TDCG\_RateHi (u; c, d)} = \begin{cases} 1 & u > d \\ \dfrac{u-c}{d-c} & c \le u \le d \\ 0 & u < c \end{cases} \qquad (3.41)$$

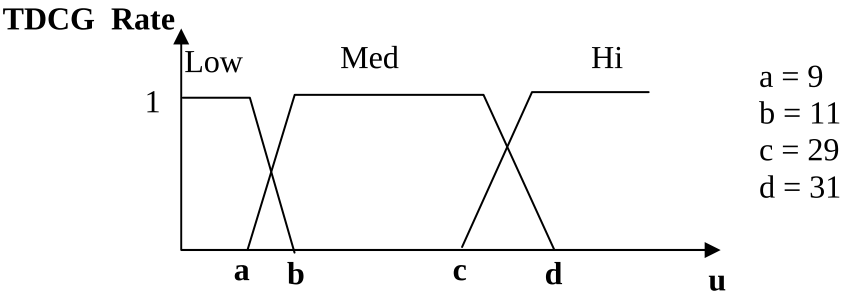


Figure 3.23 : Fuzzy membership functions used in classifying the TDCG_Rate

3.7.4 Fuzzy Inference Rules Setup

For Fuzzy TDCG method, there are a total of 12 fuzzy inference rules which can be derived from the TDCG guide in Table 3.12 and the extracted fuzzy rules are shown in Table 3.13. All of these fuzzy inference rules are used to determine 4 types of transformer operating procedures and 5 sampling intervals as shown in Table 3.14.

Table 3.13 : Fuzzy inference rules for Fuzzy TDCG

Rule 1	If TDCG=Lo and TDCG_Rate=Lo then OPA / SIA
Rule 2	If TDCG=Lo and TDCG_Rate=Med then OPA / SIQ
Rule 3	If TDCG=Lo and TDCG_Rate=Hi then OPB / SIM
Rule 4	If TDCG=Med and TDCG_Rate=Lo then OPB / SIQ
Rule 5	If TDCG=Med and TDCG_Rate=Med then OPB / SIM
Rule 6	If TDCG=Med and TDCG_Rate=Hi then OPB / SIM
Rule 7	If TDCG=Hi and TDCG_Rate=Lo then OPC / SIM
Rule 8	If TDCG=Hi and TDCG_Rate=Med then OPC / SIW
Rule 9	If TDCG=Hi and TDCG_Rate=Hi then OPC / SIW
Rule 10	If TDCG=Vhi and TDCG_Rate=Lo then OPC / SIW
Rule 11	If TDCG=Vhi and TDCG_Rate=Med then OPD / SID
Rule 12	If TDCG=Vhi and TDCG_Rate=Hi then OPD / SID

Table 3.14 : Output for Fuzzy TDCG

Sampling Interval		Operating Procedure	
SIA	6 Months	OPA	Continue normal operation.
SIQ	Quarterly	OPB	Exercise caution. Analyse for individual gases. Determine load dependence.
SIM	Monthly	OPC	Exercise caution. Analyse for individual gases. Plan outage.
SIW	Weekly	OPD	Consider removal from service.
SID	Daily		

3.7.5 Selection of Fuzzy Compositional Operator

After defining all the fuzzy inference rules, the output of the fuzzy inference can be obtained using the Mamdani's Max-Min composition operator as shown as below:

Antecedents :
Rule 1 = Min { TDCG=Lo, TDCG_Rate=Lo }
Rule 2 = Min { TDCG=Lo, TDCG_Rate=Med }
Rule 3 = Min { TDCG=Lo, TDCG_Rate=Hi }
Rule 4 = Min { TDCG=Med, TDCG_Rate=Lo }
Rule 5 = Min { TDCG=Med, TDCG_Rate=Med }
Rule 6 = Min { TDCG=Med, TDCG_Rate=Hi }
Rule 7 = Min { TDCG=Hi, TDCG_Rate=Lo }
Rule 8 = Min { TDCG=Hi, TDCG_Rate=Med }
Rule 9 = Min { TDCG=Hi, TDCG_Rate=Hi }
Rule 10 = Min { TDG=Vhi, TDCG_Rate=Lo }
Rule 11 = Min { TDCG=Vhi, TDCG_Rate=Med }
Rule 12 = Min { TDCG=Vhi, TDCG_Rate=Hi }

The consequent are computed as follows:
OP-A = Max {Rule 1,Rule 2}
OP-B = Max {Rule 3, Rule 4, Rule 5, Rule 6}
OP-C = Max {Rule 7, Rule 8, Rule 9,Rule 10}

OP-D = Max {Rule 11,Rule 12}

SIA = Max {Rule 1}
SIQ = Max {Rule 2, Rule 4}
SIM = Max {Rule 3, Rule 5, Rule 6, Rule 7}
SIW =Max {Rule 8, Rule 9, Rule 10}
SID = Max {Rule 11, Rule 12}

3.7.6 Defuzzification

For this method, 4 operating procedures and 5 sampling intervals are determined by choosing the highest degree of membership value obtained from the fuzzy inference rules. The operating procedure and sampling interval can be classified into the linguistic variable based on the degree of membership function as shown as Table 3.15.

Table 3.15 : Degree of membership function

Degree of membership	Condition
1	Most encourageable
0.75 – 0.99	Encourageable
05 – 0.74	Preferable

Example of Interpretation:

Most encourageable operating procedure :-
Exercise caution. Analyse for individual gases. Plan outage
Preferable sampling interval: - Weekl

3.8 Fuzzy Nomograph

In order to improve the accuracy of fault diagnosis, the logarithmic Nomograph method has been widely used due to its features that combine the fault gas ratio concept with the key gas threshold value in order to improve the accuracy of fault diagnosis. In essence, the Nomograph consists of a series of vertical logarithmic scales representing the concentrations of the individual gases. In the transformer fault diagnosis, straight lines will be drawn between adjacent scales to connect the point representing the values of the individual gas concentration. The slopes of these lines are the diagnostic criteria for determining the type of fault. To make the slope of the line is significant; at least one of the two tie-points should lie above the threshold value. Difficulty arises when the tie point falls exactly on the flag-point, however, by applying fuzzy technique, such problems can be overcome.

3.8.1 Identification of Fuzzy Input and Output Variable for Fuzzy Nomograph Method

In determining the fuzzy input and output variable for Fuzzy Nomograph method, the Nomograph can be split into 7 pairs of diagnostic cases based on the Nomograph chart as illustrated in Figure 3.30 while the descriptions of each pair of diagnostic case as shown in Table 3.16.

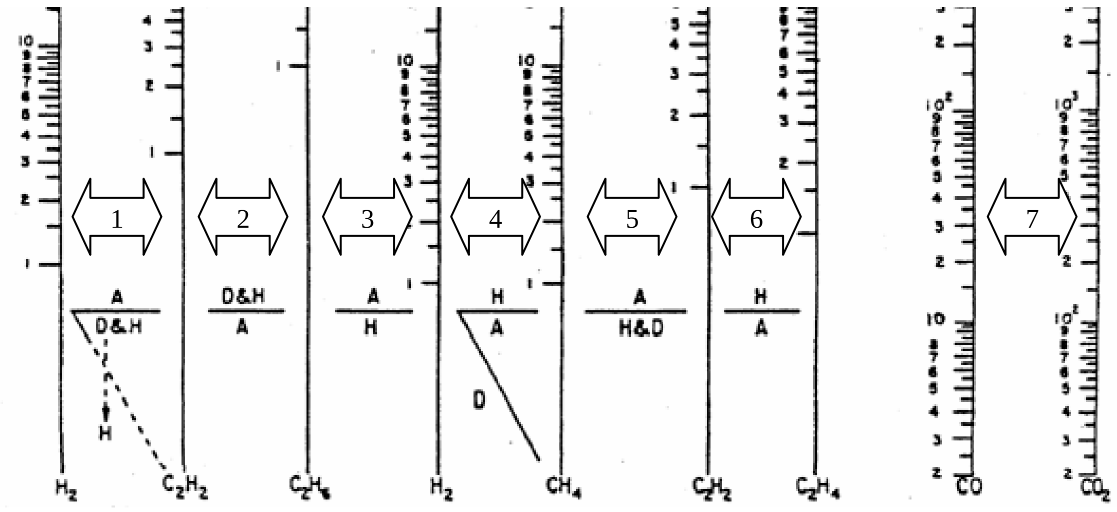


Figure 3.24: Splitting the Nomograph into 7 diagnostic cases

Table 3.16 : Description of Nomograph diagnostic case

Diagnostic Case	**Vertical Axes**	**Related Fault**
1	H_2 and C_2H_2	Arcing, Discharge and Heating, Heating
2	C_2H_2 and C_2H_6	Discharge and Heating, Arcing
3	C_2H_6 and H_2	Arcing, Heating
4	H_2 and CH_4	Heating, Arcing, Discharge
5	CH_4 and C_2H_2	Arcing, Heating and Discharge
6	C_2H_2 and C_2H_4	Heating, Arcing
7	CO and CO_2	Cellulose Insulation Breakdown

From Table 3.16, there are 14 fuzzy input variables that can be obtained from the 7 pair of diagnostic cases to determine 4 outputs which can be graphically presented in Figure 3.31.

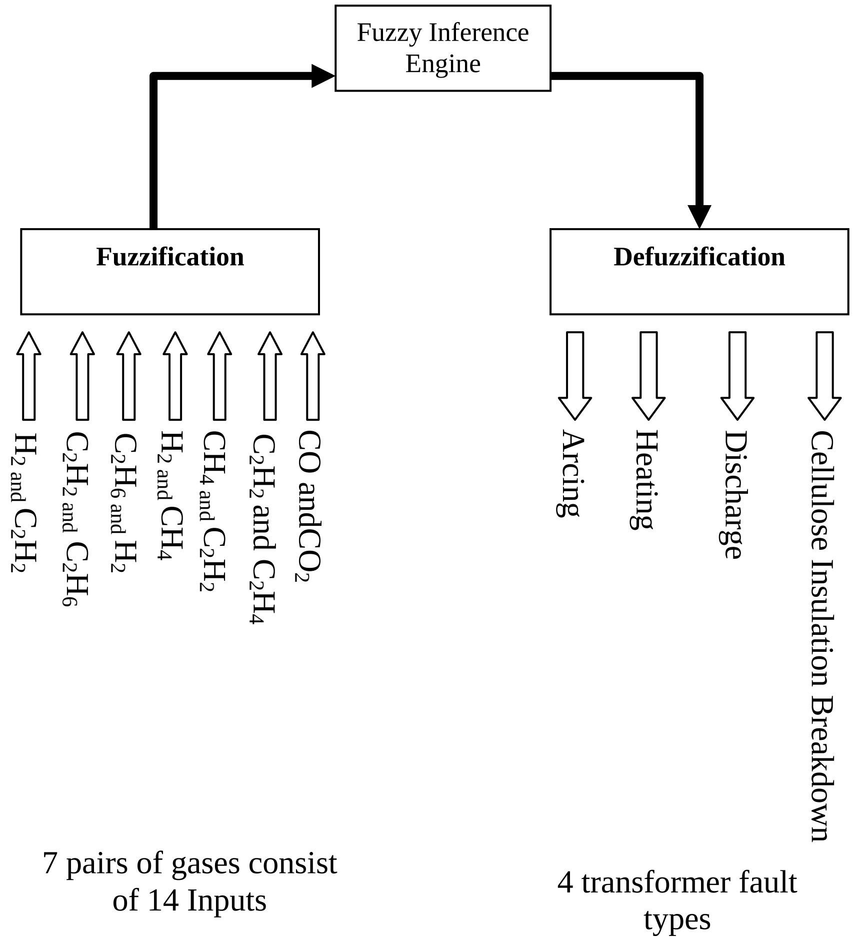


Figure 3.25 : Input and output variables for Fuzzy Nomograph

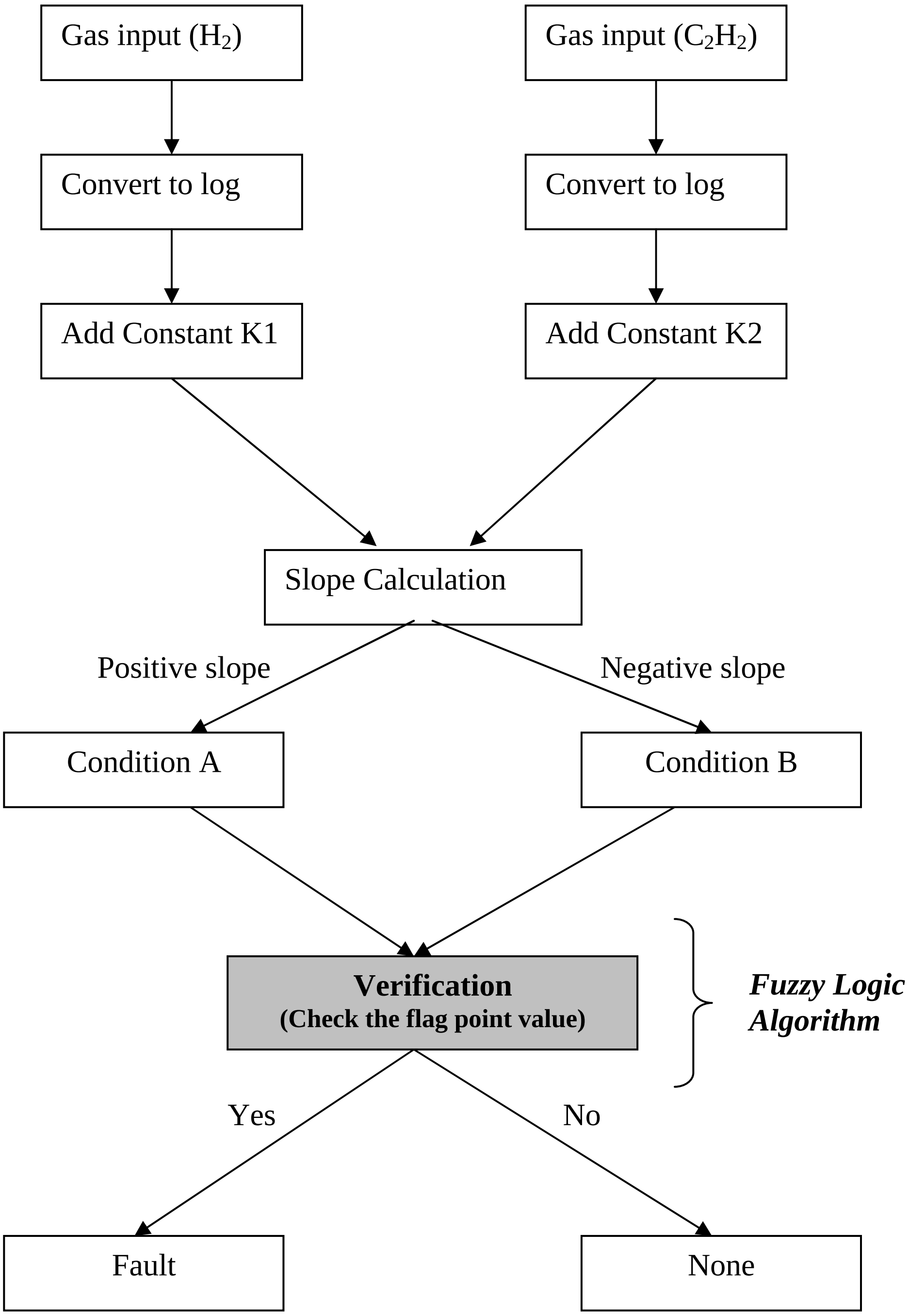


Figure 3.26 : Nomograph diagnostic process

Figure 3.32 illustrates the Nomograph diagnostic process for one of the 7 gas pair (H_2 and C_2H_2). The highlighted portion indicated the application of fuzzy logic algorithm in judging the significance of certain condition. Equation 3.37 is being used to calculate the normal slope type as shown in Figure 3.33. However, for Nomograph slope calculation, the starting point between the two axes need to be determined beforehand by adding the y1 and y2 axis with the constant k1 and k2 respectively as shown is Figure 3.34 and Equation 3.38.

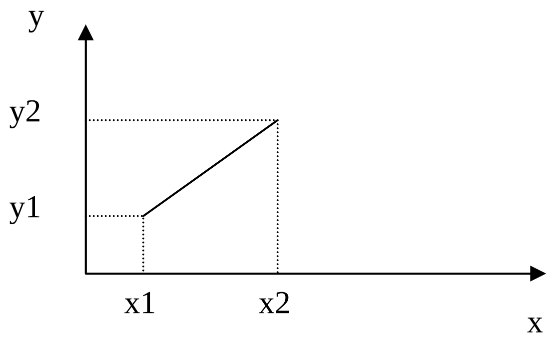


Figure 3.27 : Slope calculation

$$\text{Slope} = \frac{y2 - y1}{x2 - x1} \tag{3.37}$$

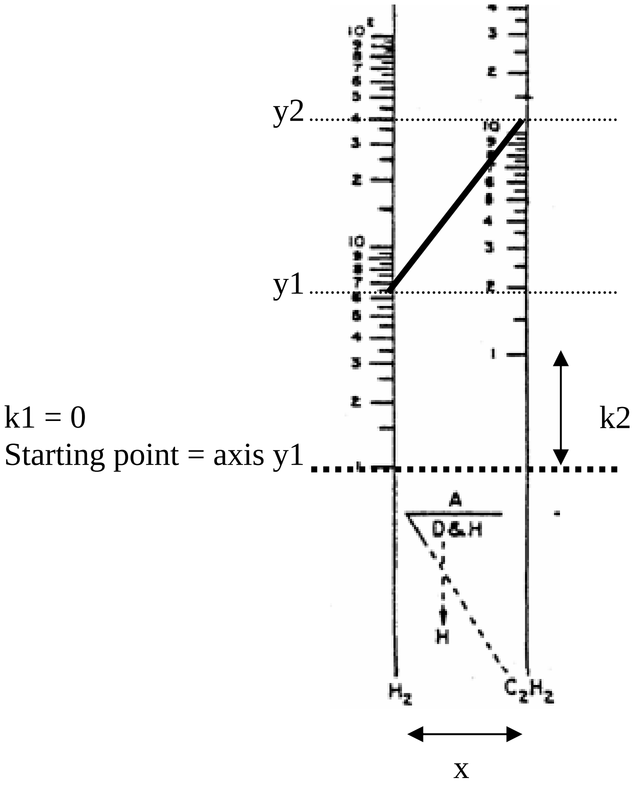


Figure 3.28 : Nomograph slope calculation

$$\text{Slope} = \frac{(y2 + k2) - (y1 + k1)}{x} \tag{3.38}$$

where x is a constant variable for all axis.

3.8.2 Quantization

This process classifies all the input variables into 2 linguistic term sets as Low (Lo) and High (Hi). Since the Key Gas method follows the IEEE Standard threshold value to evaluate the transformer, the threshold value for Nomograph flag point will follow the same threshold value to make the accuracy of both diagnostic methods can be compared in the later time. The flag point values for the entire vertical axis can be obtained from Table 3.9.

3.8.3 Assignment of Membership Functions

For the Fuzzy Nomograph diagnostic method, the appropriate membership functions applicable are both the linear function of type L-function and Γ-function. The fuzzy membership function for the Nomograph input classifications are given in Figure 3.35 for all the 14 fuzzy input variables.

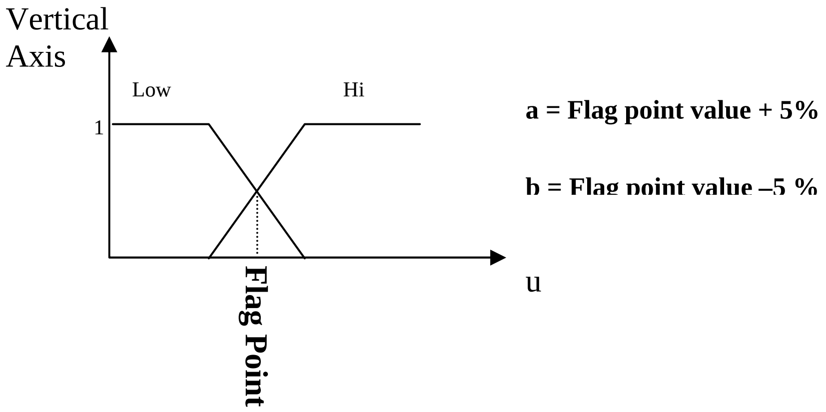


Figure 3.29 : Fuzzy membership functions used in classifying the Nomograph

The L-function is applicable for all key gases with ***low*** term set due to the membership going to one for small u and zero for large u.

$$\text{VerticalAxisLo (u; a, b)} = \begin{cases} 1 & u < a \\ \dfrac{b-u}{b-a} & a \le u \le b \\ 0 & u > b \end{cases} \tag{3.39}$$

Γ-function is applicable for all key gases with ***high*** term set due to the membership going to one for large u and zero for small u.

$$\text{VerticalAxisHi (u; c, d)} = \begin{cases} 1 & u > b \\ \dfrac{u-a}{b-a} & a \leq u \leq b \\ 0 & u < a \end{cases} \tag{3.40}$$

3.8.4 Fuzzy Inference Rules Setup

The Nomograph diagnostic approach is based on the slope of each pair of vertical axis to determine the condition of the power transformer. The slope between the vertical axis may reflex the health condition of a transformer provided. The slope must lay at least one of the flag point of the vertical axis to determined the transformer condition. Thus, the fuzzy inference rules can be derived from the statement above. There are a total of 28 fuzzy inference rules as shown in Table 3.17.

Table 3.17 : Fuzzy inference rules for Fuzzy Nomograph

Rule 1	If H_2=Hi and C_2H_2=Hi then Case1=fault
Rule 2	If H_2=Hi and C_2H_2=Lo then Case1=fault
Rule 3	If H_2=Lo and C_2H_2=Hi then Case1=fault
Rule 4	If H_2=Lo and C_2H_2=Lo then Case1=none
Rule 5	If C_2H_2=Hi and C_2H_6=Hi then Case2=fault
Rule 6	If C_2H_2=Hi and C_2H_6=Lo then Case2=fault
Rule 7	If C_2H_2=Lo and C_2H_6=Hi then Case2=fault
Rule 8	If C_2H_2=Lo and H_2=Lo then Case2=none
Rule 9	If C_2H_6=Hi and H_2=Hi then Case3=fault
Rule 10	If C_2H_6=Hi and H_2=Lo then Case3=fault
Rule 11	If C_2H_6=Lo and H_2=Hi then Case3=fault
Rule 12	If C_2H_6=Lo and H_2=Lo then Case3=none
Rule 13	If H_2=Hi and CH_4=Hi then Case4=fault
Rule 14	If H_2=Hi and CH_4=Lo then Case4=fault
Rule 15	If H_2=Lo and CH_4=Hi then Case4=fault
Rule 16	If H_2=Lo and CH_4=Lo then Case4=none
Rule 17	If CH_4=Hi and C_2H_2=Hi then Case5=fault
Rule 18	If CH_4=Hi and C_2H_2=Lo then Case5=fault
Rule 19	If CH_4=Lo and C_2H_2=Hi then Case5=fault
Rule 20	If CH_4=Lo and C_2H_2=Lo then Case5=none
Rule 21	If C_2H_2=Hi and C_2H_4=Hi then Case6=fault

Rule 22	If C_2H_2=Hi and C_2H_4=Lo then Case6=fault
Rule 23	If C_2H_2=Lo and C_2H_4=Hi then Case6=fault
Rule 24	If C_2H_2=Lo and C_2H_4=Lo then Case6=none
Rule 25	If CO=Hi and CO_2=Hi then Case7=fault
Rule 26	If CO=Hi and CO_2=Lo then Case7=fault
Rule 27	If CO=Lo and CO_2=Hi then Case7=fault
Rule 28	If CO=Lo and CO_2=Lo then Case7=none

3.8.5 Selection of Fuzzy Compositional Operator

The output of the fuzzy inference can be obtained using the Mamdani's Max-Min composition technique as shown as follows:

Antecedent:

Rule 1 = Min{ H_2=Hi and C_2H_2=Hi }
Rule 2 = Min{ H_2=Hi and C_2H_2=Lo }
Rule 3 = Min{ H_2=Lo and C_2H_2=Hi }
Rule 4 = Min{ H_2=Lo and C_2H_2=Lo }
Rule 5 = Min{ C_2H_2=Hi and C_2H_6=Hi }
Rule 6 = Min{ C_2H_2=Hi and C_2H_6=Lo }
Rule 7 = Min{ C_2H_2=Lo and C_2H_6=Hi }
Rule 8 = Min{ C_2H_2=Lo and H_2=Lo }
Rule 9 = Min{ C_2H_6=Hi and H_2=Hi }
Rule 10 = Min{ C_2H_6=Hi and H_2=Lo }
Rule 11 = Min{ C_2H_6=Lo and H_2=Hi }
Rule 12 = Min{ C_2H_6=Lo and H_2=Lo }
Rule 13 = Min{ H_2=Hi and CH_4=Hi }
Rule 14 = Min{ H_2=Hi and CH_4=Lo }
Rule 15 = Min{ H_2=Lo and CH_4=Hi }
Rule 16 = Min{ H_2=Lo and CH_4=Lo }
Rule 17 = Min{ CH_4=Hi and C_2H_2=Hi }
Rule 18 = Min{ CH_4=Hi and C_2H_2=Lo }
Rule 19 = Min{ CH_4=Lo and C_2H_2=Hi }
Rule 20 = Min{ CH_4=Lo and C_2H_2=Lo }

Rule 21 = Min{ C_2H_2=Hi and C_2H_4=Hi }

Rule 22 = Min{ C_2H_2=Hi and C_2H_4=Lo }

Rule 23 = Min{ C_2H_2=Lo and C_2H_4=Hi }

Rule 24 = Min{ C_2H_2=Lo and C_2H_4=Lo }

Rule 25 = Min{ CO=Hi and CO_2=Hi }

Rule 26 = Min{ CO=Hi and CO_2=Lo }

Rule 27 = Min{ CO=Lo and CO_2=Hi }

Rule 28 = Min{ CO=Lo and CO_2=Lo }

The consequent are computed as follows:

Case1_Significant = Max {Rule 1, Rule 2, Rule 3}

Case2_Significant = Max {Rule 5, Rule 6, Rule 7}

Case3_Significant = Max {Rule 9, Rule 10, Rule 11}

Case4_Significant = Max {Rule 13, Rule 14, Rule 15}

Case5_Significant = Max {Rule 17, Rule 18, Rule 19}

Case6_Significant = Max {Rule 21, Rule 22, Rule 23}

Case7_Significant = Max {Rule 25, Rule 26, Rule 27}

3.8.6 Defuzzification

Fuzzy diagnosis system uses the Max-membership method in the defuzzification process where the candidate which has the maximum degree of membership function is the winner. For Fuzzy Nomograph, 4 levels of severity will be determined based on the degree of membership function as listed in Table 3.18.

Table 3.18 : Degree of membership function

Degree of membership	Condition
0.8-1	Highly Significant
0.56-0.79	Significant
04-0.55	Slightly Significant
0-0.39	Not Significant

Example of Fuzzy Nomograph:

This example only shows the H_2 and CH_4 vertical axes. For this example, the H_2 flag point value is 100ppm while the CH_4 flag point value is 78ppm and the H_2 value is 102ppm and the CH_4 value is 74ppm. Figure 3.36 illustrates the Nomograph plotting for axes H_2 and CH_4 based on the value and flag point mention above.

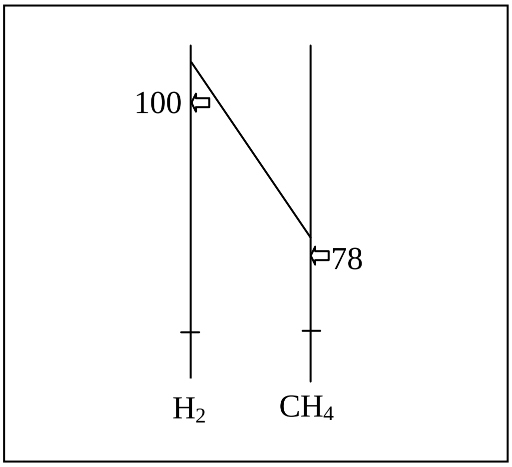


Figure 3.30 : Nomograph for H_2 and CH_4

Nomograph Interpretation:

Slope = - 0.06

Fault = Arcing

Composition:

Significant = Max {0.125, 0.7, 0.125} = 0.7

Fuzzy Interpretation:

Significant of fault Arcing

3.9 Conclusion

The use of artificial intelligent techniques such as fuzzy logic and neural networks has now been widely considered in many applications as they can provide more human-liked interpretation in solving problems. The technique of fuzzy logic has helped to overcome difficulties in setting boundary conditions of the gas-ratios and also allows the rules to be configured in a more natural language-type of structure which is more applicable and widely accepted. In addition, the number of rules can also be reduced significantly when compared to conventional “if-then” method which is rather impractical. With the advantage of fuzzy logic algorithm incorporated with the DGA fault diagnostic methods, it is hoped that an early fault detection can be fulfilled to reduce the risk of transformer explosion which cost lost of revenue and harm to human life.

CHAPTER II

LITERATURE REVIEW

The Dissolved Gas Analysis is a diagnostic and maintenance tool used in machinery. Through this method, gases are studied to give an early indication of transformer abnormal behavior. For the last 20 years, this method is widely used for detecting and diagnosing the incipient faults of power transformers [5,6]. Its effectiveness has been proven by a lot of well known electrical testing laboratories or institutions such as The Institute of Electrical and Electronics Engineers (IEEE), Central Electricity Generating Board of Great Britain (CEGB), International Electrotechnical Commission (IEC), etc.. Today, numbers of diagnostic methods based on the DGA have been proposed by researchers in the power transmission field from all over the world. However, these diagnostic methods are usually not compatible used in Malaysia and operate only under constraint conditions. In this research, four common diagnostic methods which can be conveniently applied to any operating environment and transformer were selected and will be detail discussed in this chapter. The four most famous DGA fault diagnostic methods are Rogers Ratio, Key Gas, Total Dissolved Combustible Gas (TDCG) and Logarithmic Nomograph methods.

2.1 The Rogers Ratio Method

During a transformer daily operation, some unseen and unexpected faults may occur [9]. When a fault occurs, an abnormally high dissipation of energy is emitted usually at one point in the transformer. This high energy can cause a chemical degradation of the insulating oil. Consequently, fault gases are released from this insulating medium. These gases are highly soluble in oil and will remain dissolved indefinitely. In fact, the production n of a mixture of hydrocarbon gases dependent on the energy or temperature generated by the fault. Hence, the relation between the dissolved gases, energy and the corresponding fault type can be viewed as follows.

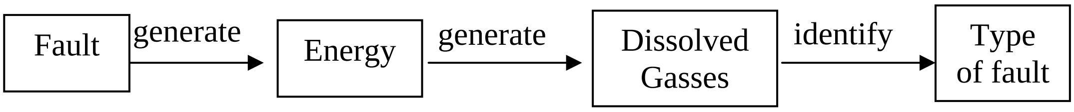


Figure 2.1 : Relation between dissolved gasses and fault type

Obviously, different types of fault may generate a different mixture of gases. Normally, the distribution of the fault gases can be related to the type of fault and the gas generation rate can indicate the severity of the fault. However, the gas generation rate can only be monitored using online monitoring techniques.

In 1974, Ron Rogers introduced a diagnostic method based on the fault gases generating rate and this method are known as Rogers Ratio method and now is widely use in the field of DGA fault diagnostic [15]. This method use the 4-digit ratio code generated from the 5 fault gases which are Acetylene, Ethylene, Methane, Hydrogen and Ethane to determine 15 transformer conditions as shown in the Table 2.1. Ron Rogers diagnostic method can be calculated from the formula below:

$$\mathrm{AE} = \frac{\mathit{Acethylene}}{\mathit{Ethylene}} \qquad \mathrm{MH} = \frac{\mathit{Methane}}{\mathit{Hydrogen}} \qquad \mathrm{EE} = \frac{\mathit{Ethylene}}{\mathit{Ethane}} \qquad \mathrm{EM} = \frac{\mathit{Ethane}}{\mathit{Methane}} \tag{2.0}$$

Table 2.1: below is the ratio range codes and the diagnostic code to describe the transformer condition after the calculation is made.

Table 2.1 : Ratio range codes and diagnostic codes [15]

C_2H_2/ C_2H_4	CH_4/ H_2	C_2H_4/ C_2H_6	C_2H_6/ CH_4	
AE	MH	EE	EM	Ratio Range
0	5	0	0	< 0.1
1	0	0	0	0.1 to < 1.0
1	1	1	1	1.0 to 3.0
2	2	2	1	> 3.0
Diagnostic Code				Fault
0	0	0	0	No fault: normal deterioration
0	5	0	0	Partial discharges of low energy density or hydrolysis
1	5	0	0	Partial discharges of high energy density, possibly with tracking
0	5	1	0	Coincidental partial discharges and conductor overheating
0	5	0	1	Partial discharges of increasing energy density
1>2	0	0	0	Low energy discharge: flashover without power follow through
1>2	0	1	0	Low energy discharge: continuous sparking to floating potential
1>2	0	2	0	High energy discharge: arc with power follow through
0	0	1	0	Insulated conductor overheating
0	0	1	1	Complex thermal hotspot and conductor overheating
1	0	0	1	Coincidental thermal hotspot and low energy discharge
1	1	0	0	
0	1	0	0	Thermal fault of low temperature range < 150^0C
0	0>2	0	1	Thermal fault of temperature range 100 - 200^0C
0	1	1	0	Thermal fault of temperature range temperature range 150 - 300^0C overheating of copper due to eddy currents.
0	1>2	2	0	Thermal fault of high temperature range temperature range 300 - 700^0C: bad contacts/ joints (pyrolytic carbon formation): core and tank circulating currents.

The example below illustrates the calculation for the Rogers Ratio diagnostic method.

Example :

Acetylene = 117 ppm	Ethylene = 36 ppm	Hydrogen = 153 ppm
Methane = 23 ppm	Ethane = 3 ppm	

$AE = \frac{113}{36} = 3.138$ Ratio code = 2

$MH = \frac{23}{153} = 0.150$ Ratio code = 0

$EE = \frac{36}{3} = 12$ Ratio code = 2

$EM = \frac{3}{23} = 0.130$ Ratio code = 0

From these calculations, the 4-digit ratio code is “2020” and based on the 4-digit code, the interpretation is *“High energy discharge: arc with power follow through”*.

However, before the Rogers Ratio calculation, concentrations of the necessary gasses have to be obtained beforehand. The process of synthesizing the related gasses from the insulating oil is named chromatographic analysis. In this analysis, steps such as separation, identification and quantitative determination of the gasses in the unit of part-per-million (ppm) are carried out in a properly equipped laboratory. After these steps are done, the type of gas with its concentration can be used for further analysis.

2.2 The Key Gas Method

The Key Gas method employs a set of rules to diagnose abnormalities such as Thermal, Corona or Arcing problems. It is a reliable diagnostic method because it can diagnose the condition of the transformer even though when only a few gases are obtained from the oil sample.

During the transformer operations, gases are produced from the degradation of the insulating oil as a result of extremely high temperatures. This high temperature can be due to overheated area of windings or bad connections and subsequently caused a high contact resistance or arcing within the main tank. The principle of the Key Gas method is based on the quantity of fault gases released from the insulating oil when a fault occurs. Every fault occurred will increase the temperature in the power transformer. The presence of the fault gases will break the link or relation of the insulating oil chemical structure depending on the temperature or energy produced. Different levels of temperature will release different type of fault gases dissolved in the insulating oil. For example, under slight overheating at about 130^{o}C, some Methane and Hydrogen gases are produced and as the temperature increases, Ethane is formed in higher relative quantities with rising temperature between 350-400^{o}C. If the temperature continues to rise up until 400^{o}C or higher, Ethylene begins to form and Acetylene will be released when the temperature reaches 700^{o}C as shown in Table 2.2.

Table 2.2 : Relation of fault gases and temperature

Temperature range (^{o}C)	**Fault gas**
130 – 150	Hydrogen (H_2), Methane (CH_4)
350 – 400	Ethane (CH_6)
400 – 600	Ethylene (C_2H_4)
> 700	Acetylene (C_2H_2)

The presence of the fault gases is important aspect in fault detection process because it corresponds consistently to the temperature generated by certain fault. Thus, based on the relation of fault gases, a decision can be made such as the presence of gas Acetylene which may indicate fault Arcing if it is above certain limit in the insulation oil [6, 9]. In addition, the identification of Hydrogen in the presence of Methane may indicate corona or partial discharge. If corona developed into low energy sparking, a higher temperature is detected which lead to the additional presence of Acetylene. On the other hand, if sparking escalates to Arcing, the presence of Ethylene can also be detected. Furthermore, when Arcing takes place in the presence of cellulose, the high temperature deterioration of the solid insulation also releases carbon monoxide and carbon dioxide into the oil. Over the years, there have been a lot of experts looking into these fields of research and the findings are quite useful and have been widely accepted as an IEEE standard (C57.104-1991) [5]. The key gases and its relation to the types of faults are listed in Table 2.3.

Table 2.3: Key Gases fault relation

Gases	**Faults**
H_2	Corona
C_2H_2	Arcing
O_2	Non-fault Related Gas
N_2	Non-fault Related Gas
CH_4 & C_2H_6	Low Temperature Oil Breakdown
C_2H_4	High Temperature Oil Breakdown
CO_2 & CO	Cellulose Insulation Breakdown

In the Key Gas method, related fault would not always occurred despite the existence of certain fault gases in oil. The fault gases may sometimes be generated during normal operation and thus, the condition of the transformer cannot be judged just based on the presence of the fault gases without taking into consideration its concentration in parts per million units. According to the IEEE standard (C57.104-1991) [5], all the fault gases have their own norm value in normal and in faulty condition and the norm value varies due to different operating conditions, manufacturers and environmental factors such as humidity and weather. Due to this, different institutions from different countries have set their own sets of norm values in fault diagnosis. Table 2.4 shows the comparison of the norm value of the British Standards Institution (BSI) [6] and the IEEE standard (USA) [5].

Table 2.4 : Fault gases norm value comparison between the IEEE and the BSI standard [5,6]

Gases	**IEEE (C57.104-1991) ppm**	**BSI (BS 5800 –1979) ppm**
H_2	100	125
C_2H_2	35	25
CH_4	120	75
C_2H_4	50	35
C_2H_6	65	75
CO	350	850

In this project, the IEEE norm value has been selected for Key Gas fault diagnostic method. However, this set of norm value can be altered easily from time to time until the best norm value that suits the transformer operating environment is found. The Key Gas method function interpretation is illustrated as follows:

Example:

Fault gases concentration in ppm.

Acetylene = 117 ppm	Ethylene = 36 ppm	Hydrogen = 153 ppm
Methane = 23 ppm	Ethane = 3 ppm	

Interpretation :

Gas Acetylene and Hydrogen are over norm value, possibly due to fault arcing and corona [6, 9].

In comparison with the Roger Ratio method, the Key Gas method used the individual gas rather then the calculation of the gas ratios for detecting fault conditions. The Ratio Roger method requires all 5 necessary gas ratios to be calculated correctly for interpretations. However, if the gas concentration value is lacking, the Roger Ratio method might not give result. Therefore, the Key Gas method is preferable then the Roger Ratio method.

2.3 Total Dissolved Combustible Gas

Total Dissolved Combustible Gas (TDCG) is another method using DGA principle. TDCG used the sum of the 6 fault gases value and the TDCG generation rate to determine the operating procedure for the prediction of suitable oil sampling interval as shown in Table 2.5 below:

Table 2.5: Action based on TDCG

TDCG	**TDCG Rates (ppm/day)**	**Sampling Intervals and Operating Procedures for Gas Generation Rates**	
		Sampling Interval	**Operating Procedure**
< 720	> 30	Monthly	Exercise caution. Analyse for individual gases. Determine load dependence.
	10 – 30	Quarterly	Continue normal operation.
	< 10	6 Month	
721 – 1920	> 30	Monthly	Exercise caution. Analyse for individual gases. Determine load dependence.
	10 – 30		
	< 10	Quarterly	
1921 – 4630	> 30	Weekly	Exercise caution. Analyse for individual gases. Plan outage.
	10 – 30		
	< 10	Monthly	
> 4630	> 30	Daily	Consider removal from service.
	10 – 30		
	< 10	Weekly	Exercise caution. Analyse for individual gases. Plan outage.

The fault gases include Acetylene, Ethylene, Hydrogen, Methane, Ethane and Carbon Monoxide. The major advantage of the TDCG method compared to the other DGA diagnostic methods is that it is faster and easier to be applied. In fact, it can be used continuously to monitor a unit in order to avoid the occurrence of any unplanned outage.

The fault gases involves in the TDCG calculations are Hydrogen, Acetylene, Ethane, Ethylene, Methane and Carbon Monoxide while the TDCG rate can be calculated from the formula below:

$$TDCG = Acetylene + Ehtylene + Hygrogen + Methane + Ethane + CarbonMonoxide \tag{2.1}$$

$$TDCG\ Rate = \frac{(St - So)}{T} \tag{2.2}$$

Where St = Current TDCG So = Previous TDCG

T = Time in days

Through the analysis of the TDCG concentration and the TDCG generation rate, the condition of the transformer can be determined. However, this method can not specify the type of fault that occurs in the transformer. This method is only able to detect whether the transformer is in good or bad condition. The TDCG method only uses the sum of the combustible fault gases but does not identify which gas is actually presence. This kind of information is useful in fault diagnosis and without such information it is difficult to determine the fault of the transformer.

The example below illustrates two cases where both have the same TDCG values but with different type of faults.

Case 1 (fault corona):

Acetylene = 20 ppm	Ethylene = 15 ppm	Hydrogen = 350 ppm
Methane = 50 ppm	Ethane = 39 ppm	Carbon Monoxide = 340 ppm

TDCG = 814 (using formula 2.1)

Case 2 (fault arcing):

Acetylene = 200 ppm	Ethylene = 45 ppm	Hydrogen = 50 ppm
Methane = 94 ppm	Ethane = 55 ppm	Carbon Monoxide = 370 ppm

TDCG = 814 (using formula 2.1)

Assume that the previous TDCG is 500 oil, volume is 100 and the duration from last sampling date is 30 days. The TDCG rate can be calculated using formula 2.2 and the next sampling interval and operating procedure can be determined later.

$$\text{TDCG Rate} = \frac{(St - So)}{T}$$

$$= \frac{(814 - 500)}{30}$$

$$= 10.46$$

Sampling interval = Monthly

Operating procedure = Exercise caution. Analyze for individual gases.

Obviously the example above shows that the TDCG method has limitation in identifying the fault type. However, this method is useful to find out the oil-sampling interval which is based on the health condition of the transformer. Therefore, it can be use to compensate the conflict between excessive cost due to over sampling and to overcome danger owing to long sampling period. Due to this TDCG limitation in not able to identify the exact fault type in the transformer, the TDCG method is usually used with the Key Gas method so that the correct fault can be identified.

2.4 Logarithmic Nomograph

The logarithmic Nomograph method was developed by Church of the U.S. Bureau of Reclamation [16]. This method is the combination the fault gas ratio concept and the Key Gas threshold value in order to improve the accuracy of fault diagnosis. It was intended to provide both a graphic presentation of fault-gas data and the means to interpret its significance. The accuracy of interpretation of the fault-gas data using Nomograph has been validated over the past decade. The Nomograph consists of a series of vertical logarithmic scales representing the concentrations of the individual gases as shown in Figure 2.2.

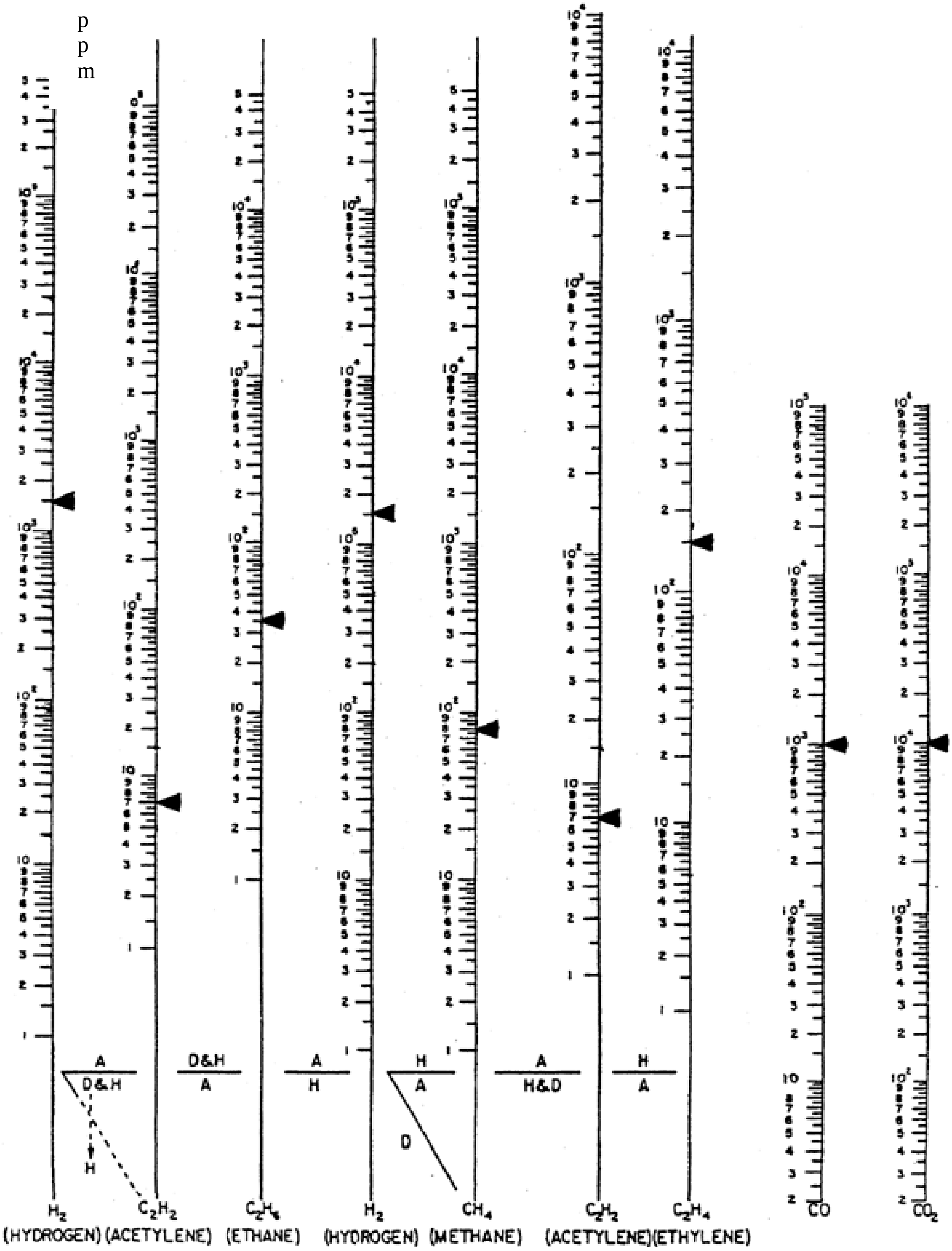


Figure 2.2: Logarithmic Nomograph

In the case of transformer fault diagnosis, straight lines will be drawn between adjacent scales to connect the points representing the values of the individual concentration. The slopes of these lines are the diagnostic criteria for determining the type of fault. The key at the bottom of the chart between the two axes indicates the fault type for the two axes. A visual comparison of the slopes of the line segments with the keys given at the bottom of the Nomograph is all that are needed to identify the type of fault. The position of the lines relative to the concentration scales provides a means of assessing the severity of the fault.

From the DGA methods, experts had successfully correlated different fault-gas ratio in the transformer. For example, the ratio of methane to hydrogen is related to three major fault types which are phyrolysis, arcing and corona. If the ratio is greater than one, phyrolysis is indicated; ration between the limit of 0.1 to 1 indicates arcing and a ratio less than 0.1 is indicates corona. Based on this theory, the Nomograph method is developed as shown in Figure 2.3 below:

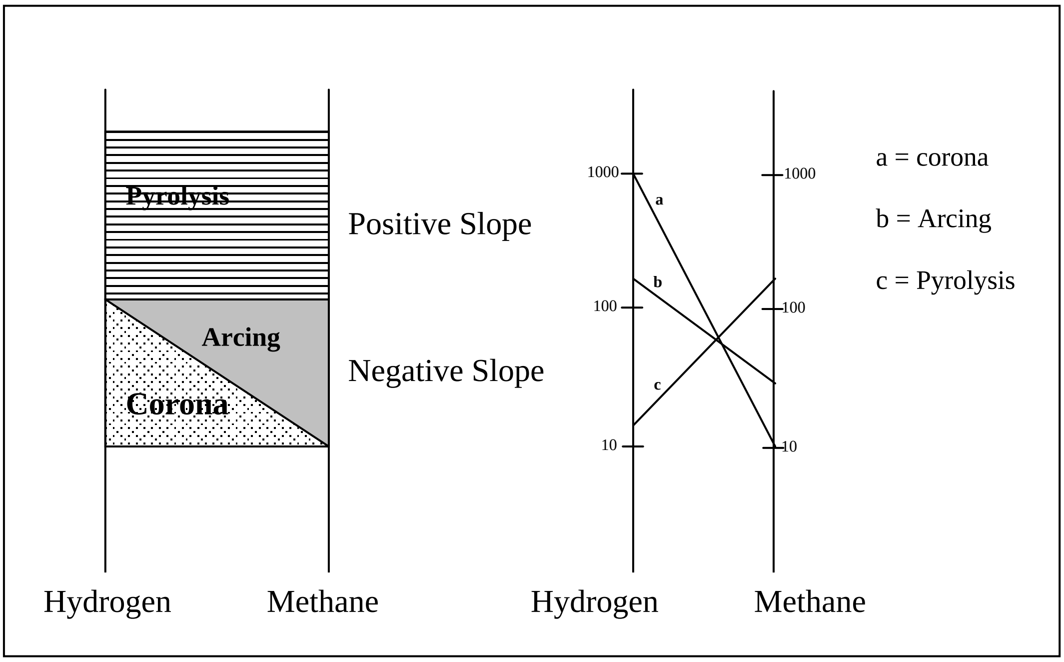


Figure 2.3: Slope of line

However, such fault gas ratio relation, is very hard to understand or interpret especially by the novice user. Therefore, the U.S. Bureau of Reclamation had established the Nomograph method in order to simplify the fault gas ratio method [16]. This simplified method is more user-friendly in terms of fault diagnostic analysis. In this case, an examination of the slope of the line connecting the hydrogen concentration to the methane concentration would indicate the type of fault. The desired result was achieved by using identical logarithmic scales for both hydrogen and methane. Thus, connecting the points on the two appropriate scales corresponding to a hydrogen concentration of 100 ppm and a methane concentration of 100 ppm forms a horizontal line. This line corresponds to a methane-hydrogen ratio of 1. A ratio less than 1 indicates that the problem is pyrolysis. Negative slope in the range of 0 to –1 corresponds to a ratio of hydrogen to methane in the range of 1 to 10 indicating arcing. A negative slope greater than –1 corresponding to a hydrogen to methane ratio greater than 10 indicates corona or partial discharge.

The other ratios of concentration obtained from the DGA are treated in a similar manner to form a complete Nomograph diagnostic method. The ratios involved in Nomograph are hydrogen-acetylene, acetylene-ethane, ethane-hydrogen, hydrogen-methane, methane-acetylene and acetylene-ethylene as shown in Figure 2.2. The presence of carbon monoxide and carbon dioxide in an oil sample may indicate the fault of cellulose insulation breakdown. The ratio of carbon monoxide to carbon dioxide should not exceed 0.1 in normal deterioration. A negative slope between the scales for carbon monoxide and carbon dioxide indicates ratio of carbon monoxide and carbon dioxide greater than 0.1. This condition signifies an accelerated rate of decomposition of cellulose that can be ascribed to the higher temperatures associated with a fault.

To use the Nomograph, the parts-per-million values of the fault gases obtained from DGA are plotted in the vertical scales. The diagnostic keys which located at the bottom of the scales are used to interpret the mode of failure according to the slope of the line connecting the plotted points. For example, the vertical axes of the gas hydrogen and acetylene can be correlated to the three major fault types. The positive slope indicates the fault of arcing. Meanwhile, if the slope is between 0 and –1 it is due to partial discharge or heating, and if the slope is steeper than –1 then it is due to heating. Each vertical scale has a threshold value labeled with an arrow. For the slope of a line to be considered significant, at least one of the two tie-points should lie above the threshold value. If neither tie-point lie above a threshold value then the fault is considered not significant. For this project, the norm value of the IEEE standard (C57.104-1991) has been used as the threshold value. Figure 2.4 and Figure 2.5 illustrate an example of the fault diagnosis using the Nomograph method.

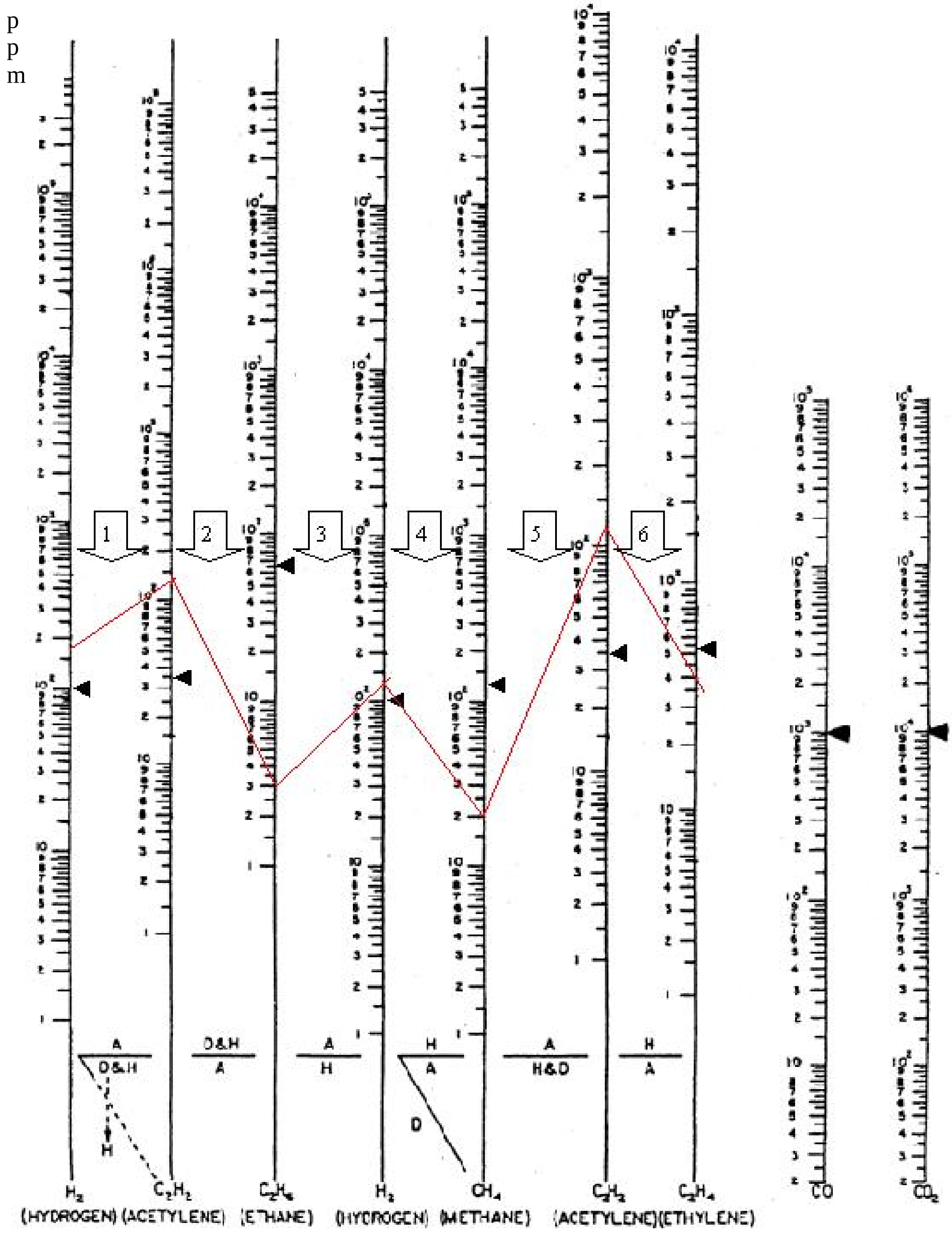


Figure 2.4 : Fault diagnosis using Nomograph method (Arcing case)

Figure 2.4 shows the Nomograph plotting for the DGA test result below:

Acetylene = 117 ppm
Ethylene = 36 ppm
Hydrogen = 153 ppm
Methane = 23 ppm
Ethane = 3 ppm

From Figure 2.4, the flag a point for each gas in the vertical axes have been marked based on the IEEE standard. The detail interpretation for each pair of vertical axes is shown as Table 2.6.

Table 2.6: Summary of diagnosis using Nomograph method (Arcing)

Indicator in figure 2.2	**Vertical Axes**	**Slope**	**Fault**	**Significant**
1	Hydrogen & Acetylene	Positive	Arcing	Significant
2	Acetylene & Ethane	Negative	Arcing	Significant
3	Ethane & Hydrogen	Positive	Arcing	Significant
4	Hydrogen & Methane	Negative	Arcing	Significant
5	Methane & Acetylene	Positive	Arcing	Significant
6	Acetylene & Ethylene	Negative	Arcing	Significant
Summary of diagnosis : Arcing				

Figure 2.5 shows the Nomograph plotting for the DGA test result below and the detail interpretation of each pair of vertical axes are shown in Table 2.7.

Acetylene = 20 ppm
Ethylene = 10 ppm
Hydrogen = 10 ppm
Methane = 20 ppm
Ethane = 150 ppm

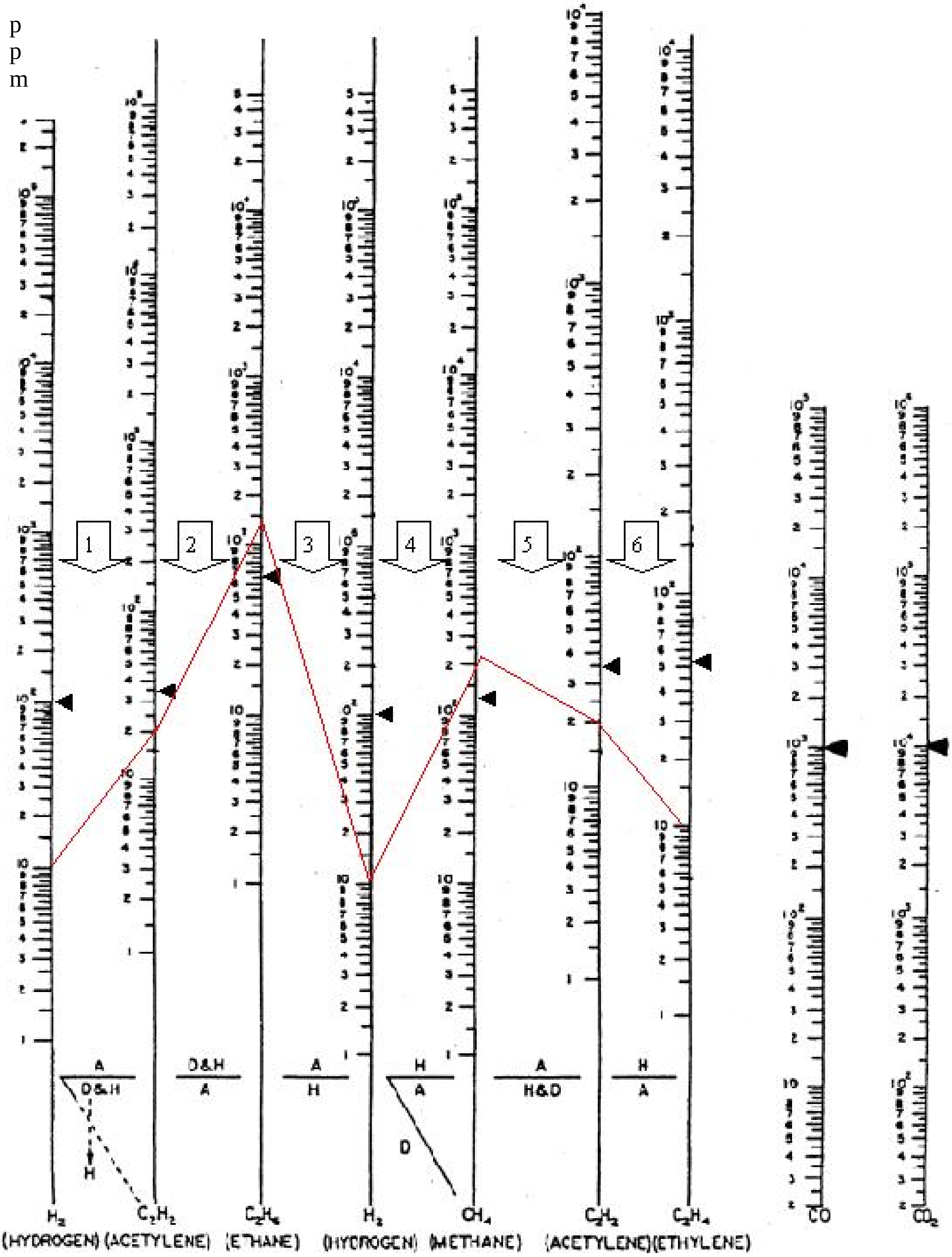


Figure 2.5 : Fault diagnosis using Nomograph method (Heating and partial discharge)

Table 2.7 : Summary of diagnosis using Nomograph method (Heating)

Indicator in figure 2.2	**Vertical Axes**	**Slope**	**Fault**	**Significant**
1	Hydrogen & Acetylene	Positive	Arcing	Not Significant
2	Acetylene & Ethane	Positive	Discharge / Heating	Significant
3	Ethane & Hydrogen	Negative	Heating	Significant
4	Hydrogen & Methane	Positive	Heating	Significant
5	Methane & Acetylene	Negative	Heating / Discharge	Significant
6	Acetylene & Ethylene	Negative	Arcing	Not Significant
Summary of diagnosis : Heating and partial discharge				

2.5 Conclusion

The DGA methodology has gained worldwide acceptance during the past 20 years as a diagnostic tool for fault detecting incipient fault in oil-filled power transformers. This acceptance reflects a unique ability of the DGA to detect faults at the earliest possible stage and to distinguish among different kinds of fault that occur inside the transformer such as arcing, heating and partial discharge. However, the DGA diagnostic methods that are invented by different experts from all around the world have their own unique advantages in fault diagnosis of power transformer. All the diagnostic methods discussed above have their own unique features and advantages that contributed to the transformer fault detection. In order to build a robust and reliable fault diagnostic system, all the 4 DGA diagnostic methods discussed above will be utilized to form the TIDS architecture. This is needed as each of the DGA methods has their own strength and weakness. For example, Rogers Ratio method can diagnose more fault types compare to Key Gas and Nomograph method but Rogers Ratio method is only applicable when all the 5 fault gases is presented in order to calculate the 4 ratio code. When certain fault gases can not be detected, the Key Gas and Normograph method can be used to diagnose the condition of the transformers. Thus, combining all the 4 DGA methods to construct the TIDS architecture may improve the reliability of the fault diagnostic system. Table 2.8 below shows the comparison among the 4 most widely used DGA diagnostic methods.

Table 2.8: Comparison of DGA diagnostic methods

Features	Rogers Ratio	Key Gas	TDCG	Nomograph
Data can be quickly and easily interpreted		✓	✓	✓
Early detection of fault	✓	✓	✓	✓
Fault types can be identify accurately	✓	✓		✓
Able to identify in detail a specific fault type	✓			
Can interpret based on individual or incomplete fault gases		✓		✓
Oil volume independent	✓			✓
Transformer type independent	✓		✓	✓

CHAPTER V

DATA AND DISCUSSION

The current version of ADAPT consists of a fuzzy rule base which have been coded from expert knowledge. A more dynamic rule base can be realized where the rules are automatically generated from the past data. However, due to the small number of past data, it is difficult to design such a system. A technique based on data mining that can generate the required rules will be discussed in this chapter. Unfortunately, it is not implemented in ADAPT due to time constraint and insufficient of data. In this chapter, an overview of Data Mining (DM) concept will be described, in which the difference of association rule and characteristic rule is given. Then, the objectives of utilising DM in this project are specified. In the next section, a description of a DM algorithm used in this approach, namely the Apriori algorithm is given. Later, a series of screen shot illustrating the rule generation process is presented. Consequently, an experiment and analysis will be carried out to prove the rules validity and observe the benefits of obtaining additional rules. Then, the advantages and disadvantages of applying DM will be listed. Finally, the benefits of DM in extracting strong correlation of transformer diagnostic rules will be highlighted.

5.1 Data Mining Overview

Data mining (DM) has recently emerged to be an active research area among the researchers from statistics, machine learning, neural networks and etc. The main objective of DM is to discover information about the data that helps to explain the data, support decisions, or predict future outcomes. Very often, the term DM is used interchangeably with Knowledge Discovery in Databases (KDD) in the literature. Nevertheless, KDD and DM have distinct meaning. KDD is referred to the overall process of discovering useful knowledge in which several steps are involved such as target data selection, data pre-processing, data transformation, data mining and patterns or rules interpretation. Meanwhile, DM is a sub-process of the whole KDD which focused in applying DM techniques, tools or algorithms to mine hidden knowledge from data. Their distinction can be further proven by Fayyad [26]:

> *KDD process is the process of using data mining methods (algorithms) to extract (identify) what is deemed knowledge according to the specifications of measures and thresholds, using the database F along with any required preprocessing, subsampling, and transformations of F.*
>
> *Data Mining is a step in the KDD process consisting of particular data mining algorithms that, under some acceptable computational efficiency limitations, produces a particular enumeration of patterns* E_j *over F.*

5.1.1 Association Rule Mining

DM is initially being used to mine association rules. The first application of DM is to build relation among items bought together during a supermarket visit. This application is named “market basket analysis”. Given $I = \{i_1, i_2, \ldots, i_n\}$ be a set of items, an association rule is a condition of the form $X \rightarrow Y$ where $X \subseteq I$ and $Y \subseteq I$ are two sets of items, such that $X \cap Y = \phi$. With the discovery of items association, it is helpful in customer segmentation, cross marketing, catalogue design and product placement.

Due to the unique strength of the DM technique in discovering strong correlations from databases and the appropriateness of this technique in this project, this technique is used to extract rules that might reveal the relation between the test result and the fault type in the power transformers. Thus, instead of supplement the fuzzy rule based with the expert defined rules which is currently being done, the extracted rules can actually be included into the rule base to furnish it with some unexpected or hidden strong correlations. These rules are named characteristic rules whereby to some extend, they exhibit the characteristics of the class.

5.1.2 Characteristic Rule Mining

Characteristic rules are descriptions of characteristics or properties of the classes. Usually, the descriptions are in the form of abstractions or generalisation. Precisely, a characteristic rule can be presented in logical form of X → Y, similar to an association rule. However, X in characteristic rule represents a set of condition attributes while Y represents the predictive attribute of the problem at hand. For transformer fault analysis, the ultimate objective is to build a set of characteristic rule for each fault type. Consequently through these rules, the fault type for an oil specimen can be predicted by analysing its test results. An example of possible characteristic rule for arcing is *“if* C_2H_2 *= ‘very high’ and* C_2H_6 *= ‘normal’ and* CH_4 *= ‘normal’ and* C_2H_4 *= ‘normal’ and CO = ‘high’, then fault type = ‘arching’”*.

5.2 Objectives of Data Mining

Currently, the fuzzy rule base of the TIDS is designed or coded from knowledge of the experts. These rules are defined by experts after many years of research. When data are collected in ADAPT, potential new correlations between test result and fault types may exist. Experts might need more time to discover these significant correlations due to the voluminous amount of data. Therefore, as DM is an automatic knowledge discovery method, it is hoped that by utilising this method, potential diagnostic rules from an overwhelming size of data could be extracted. Consequently, the fuzzy rule based could be improved by these rules besides the expert's defined rules. Some related work that uses DM to maintain a knowledge base can be seen from Holmes [27]. Ultimately, the objective of utilising the DM technique is to extract unforeseen rules hidden among the mountainous data and thus, the fuzzy rule based could be cross-checked and added.

To accomplish this objective, an intelligent database engine (IDE) developed at the Centre for Artificial Intelligence and Robotics (CAIRO) of the University Of Technology Malaysia (UTM) is utilised[28]. IDE is an automatic rule discovery system that has capability to derive a descriptive model from a set of data. It incorporates a famous DM algorithm, name the Apriori algorithm to dig out significant relation between condition and consequence. Thus, IDE is used to identify frequent patterns in the test results that reflect the fault types. When the patterns and fault types relation have been developed, future instance can be characterised into one of the finite fault type accurately.

5.3 The Apriori Algorithm

The Apriori algorithm is initiated by Agrawal and Srikant [29]. It is initially used in mining association rules in market basket analysis cases. To apply the Apriori algorithm for mining characteristic rules, some modifications are needed. However, the necessary modifications have been done in the IDE work at CAIRO [28].

Basically, the Apriori algorithm introduces two concepts: support and confidence. Support indicates the frequency of the occurring patterns while confidence denotes the strength of the implications in the rules. Given X as the test result and Y as the fault type, support and confidence can be obtained by using formulas as follows:

$$\text{support} = \frac{XY}{Y} * 100\% \tag{5.1}$$

$$\text{confidence} = \frac{XY}{X} * 100\% \tag{5.2}$$

Thus, mining characteristic rules is a problem of finding large criteria set (conjunction of test result) that satisfy user defined minimum support (minsup) and finding a strong relation (correlation between test result and fault type) that satisfy user defined minimum confidence (minconf).

5.3.1 Algorithm

For a clear understanding of the algorithm, some nomenclature of the Apriori algorithm is presented in Table 5.1.

Table 5.1: Nomenclature of Apriori algorithm

Symbol	Description
$X = \{x_1, x_2 \ldots x_n\}$	Set of test results; antecedence of the rule.
$Y = \{y_1, y_2 .. y_n\}$	Fault type; consequence of the rule.
$D = \{r_1, r_2 \ldots r_n\}$	Database and records, input for Apriori algorithm
L_k	Set of large k-criteria-sets (those with minimum suport) Each member of this set has two fields: 1. Criteria-set (gas = concentration) 2. Support count
C_k	Set of candidate k-criteria-sets (potentially large criteria-sets) Each member of this set has two fields: 1. Criteria-set (gas = concentration) 2. Support count
Minsup	User specified minimum support (1-100%)
Minconf	User specified minimum confidence (1-100%)

The problem of discovering classification rules can be decomposed into two sub-problems:

Part I: Find all sets of criteria-sets that have support above a certain minimum. The support of a criteria-set is the number of records that contain the criteria-set. Criteria-sets with minimum support are called large criteria-sets, and all others small criteria-set.

Part II: Use the large criteria-sets to generate the desired rules. Here, each large criteria-set is combined with the class value to calculate the confidence. The confidence of a rule is the number of records that contain the criteria-set and also contain the class value.

```
‘Part I:
‘Input: a set of evaluation criteria and the output field
‘Output: a set of large k-criteria set

1)      For each distinct value in the output field (y)
2)          Filter for records that have output field value = y
3)          Calculate the total number of record in step 2 ($N_y$)
4)          Calculate the minimum support in terms of number of records
5)
                $\min\sup = \frac{userdefined \min\sup}{100} * N_y$

6)          $L_1$ = {large 1-criteria sets}
7)          k = 2
8)          Do while $L_{k-1} \neq \phi$
9)              $C_k$ = apriori-gen($L_{k-1}$)
10)             For each $c \in C_k$
11)                 c.count = count-c(c,y)
                End for
12)             $L_k = \{c \in C_k \mid c.count \geq minsup\}$
13)             k = k + 1
            End while
13)         Final large criteria-sets = $\cup_k L_k$

‘Part II:
‘Input: a set of large k-criteria set
‘Output: a set of “if… then…” rule

14)         For each x in $L_k$
15)             calculate its confidence against the output value
16)
                    $x.conf = \frac{xy.count}{x.count} * 100$

                ‘where x.count is the count of x in y only

17)             if $x.conf \geq minconf$ then
18)                 output rule as if x then y
                end if
19)         End for
20)     End for
```

```
Apriori-gen($L_{k-1}$)
For each pair of $l_{k-1}^{1}$, $l_{k-1}^{2}$ $\in$ Lk-1 and $l_{k-1}^{1} \neq l_{k-1}^{2}$ where their first k-2 criteria-set are the same
    Do begin
        Construct candidate criteria-set $C_k$ such that its first k-2 criteria-set are the same as $l_{k-1}^{1}$, and the last two criteria-sets are the last criteria-set of $l_{k-1}^{1}$ and the last criteria-set of $l_{k-1}^{2}$
        'All subset of the k-large criteria set must also be large
        If there is a length k-1 subset of $s_{k-1} \subset c_k$ and $s_{k-1} \notin L_{k-1}$
        Then
            Remove $c_k$
        Else
            Add $c_k$ to $C_k$
        End if
    End do
End for

Count-c(c,y)
Count-c = count the number of record in the database which satisfy the criteria below:

    antecedence = c and concequence = y
```

5.3.2 Rule Interpretation and Presentation

The rules generated by the Apriori algorithm must be interpreted after the rule generation process. By using the definition of attribute's names and values in the previous step, the rule can actually be translated into a meaningful fact. This in turn can encourage user acceptance and application in helping their daily routine. For example, bold words are in fact the interpretation of the rule. Figure 5.8 below shows the generated rules.

Rules Generated At: 3/9/00 (4:12:11 PM)
Single Support: Min Support = 10; Min Confedence = 30

Rule(s) for Result = a (Normal)
1. C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal'
(supp = 96; conf = 81)
Acetylene = normal and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = normal
Then Fault = Normal

Rule(s) for Result = b (Arcing)
1. C_2H_2 = 'high' and H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal'
(supp = 25; conf = 100)
Acetylene = high and Hydrogen = normal and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = normal
then Fault = Arcing

2. C_2H_2 = 'very high' and H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal'
(supp = 20; conf = 100)
Acetylene = veryhigh and Hydrogen = normal and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = normal
then Fault = Arcing

3. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal'
(supp = 25; conf = 85)
Acetylene = veryhigh and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = normal
then Fault = Arcing

Rule(s) for Result = c (Overheating)
1. C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'high' and C_2H_4 = 'very high' and CO = 'normal'
(supp = 12; conf = 75)
Acetylene = normal and Ethane = normal and Methane = high and Ethylene = veryhigh and Carbon Monoxide = normal
then Fault = Overheating

2. C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'very high' and CO = 'normal'
(supp = 12; conf = 100)
Acetylene = normal and Ethane = normal and Methane = normal and Ethylene = veryhigh and Carbon Monoxide = normal
then Fault = Overheating

3. C_2H_2 = 'normal' and C_2H_6 = 'very high' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal'
(supp = 12; conf = 100)
Acetylene = normal and Ethane = veryhigh and Methane = normal and Ethylene = normal and Carbon Monoxide = normal
then Fault = Overheating

Rule(s) for Result = d (Corona)

1. C_2H_2 = 'normal' and H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal'
   (supp = 22; conf = 100)
   Acetylene = normal and Hydrogen = veryhigh and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = normal
   then Fault = Corona

2. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'high'
   (supp = 17; conf = 33)
   Acetylene = veryhigh and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = high
   then Fault = Corona

Rule(s) for Result = e (Cellulose Insulation Breakdown)

1. C_2H_2 = 'high' and H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'high'
   (supp = 11; conf = 50)
   Acetylene = high and Hydrogen = normal and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = high
   then Fault = Cellulose Insulation Breakdown

2. C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'high'
   (supp = 25; conf = 88)
   Acetylene = normal and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = high
   then Fault = Cellulose Insulation Breakdown

3. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'high' and CO = 'high'
   (supp = 11; conf = 33)
   Acetylene = veryhigh and Ethane = normal and Methane = normal and Ethylene = high and Carbon Monoxide = high
   then Fault = Cellulose Insulation Breakdown

4. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH4 = 'normal' and C_2H_4 = 'normal' and CO = 'high'
   (supp = 14; conf = 33)
   Acetylene = veryhigh and Ethane = normal and Methane = normal and Ethylene = normal and Carbon Monoxide = high
   then Fault = Cellulose Insulation Breakdown

5. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'very high' and CO = 'high'
   (supp = 11; conf = 33)
   Acetylene = veryhigh and Ethane = normal and Methane = normal and Ethylene = veryhigh and Carbon Monoxide = high
   then Fault = Cellulose Insulation Breakdown

5.4 Experiment and Analysis

The dataset used in this experiment consists of 149 records and the fault types have been generalised from 14 into 5. This is done by grouping the approximately same fault types into the same categories. The grouping is done to ensure there are not too many class value exists in such a small dataset which have many failures in the result.

The experiment can be divided into two parts. First, the generated rules will be matched with the expert defined rules. The objective is to prove that extracted rules agreed with the expert knowledge. Secondly, unmatched rules are listed for further validation by experts. The experiment procedure is illustrated as in Figure 5.1 below.

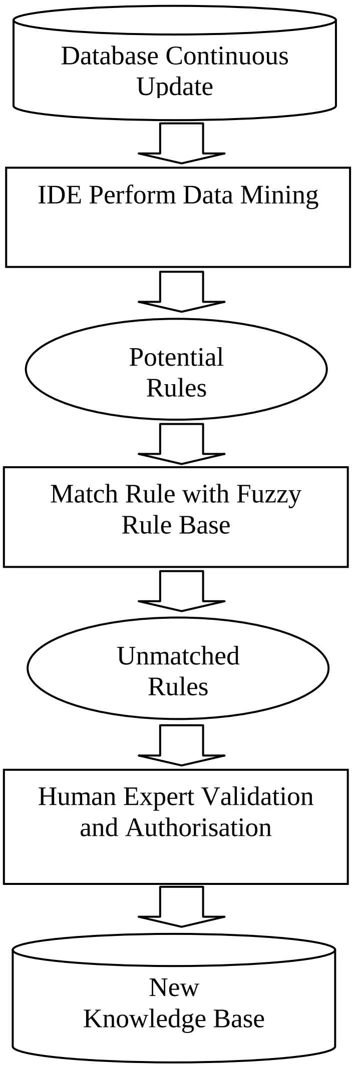


Figure 5.1: Experiment Flow

An analysis is being done to compare the validity of the extracted rules. The Key gases diagnostic method is used as a reference. In the left column of Table 5.2 are the rules defined by experts while the right column consists of the Apriori generated rules that match with expert's expectation. The degree of validity of the rules is given by the confidence and support parameter. Higher confidence rule are more significant than the lower and so as higher support rules are more significant that the lower. Also, the definition of the value range for 'normal', 'high' and 'very high' for the respective gases can be found in Table 5.2.

Table 5.2: Matched rules between the Key Gas method and the Apriori Algorithm generated rules

Key Gases Method	Apriori Extracted Rules
H_2 ≥ high → corona	C_2H_2 = 'normal' and H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal' → corona (sup = 22%, conf = 100%)
CH_4 ≥ high or C_2H_6 ≥ high → overheating	C_2H_2 = 'normal' and C_2H_6 = 'very high' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal' → overheating (sup = 12%, conf = 100%)
C_2H_4 ≥ high → overheating	C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'very high' and CO = 'normal' → overheating (sup = 12%, conf = 100%)
C_2H_2 ≥ high → arching	C_2H_2 = 'high' and H_2 = 'normal ' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal' → arching (sup = 25%, conf = 100%)
	C_2H_2 = 'very high' and H_2 = 'normal ' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal' → arching (sup = 20%, conf = 100%)
	C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal' → arching (sup = 25%, conf = 100%)
CO ≥ high → cellulose insulation breakdown	C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'high' → cellulose insulation breakdown (sup = 25%, conf = 88%)

From Table 5.2, there are 50% of the extracted rules matched with the Key Gases Diagnostic rules. Obviously, the extracted rules are valid and have high confidence of applicability. On the other hand, it is determined that expert defined rules are significant as reflected by the data.

In addition to the rules stated in Table 5.2, a list of unmatched rules has also been generated from the Apriori algorithm. These rules are considered as potential rules that might be discovered with more correlation. However, the validity of these rules highly depended on the expert validation as no means of proof is available currently. Some examples of these unmatched rules are listed as follows:

1. C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'normal' → normal (sup = 96%, conf = 81%)
2. C_2H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'high' and C_2H_4 = 'very high' and CO = 'normal' → overheating (sup = 12%, conf = 75%)
3. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'high' then → corona (sup = 17%, conf = 33%)
4. C_2H_2 = 'high' and H_2 = 'normal' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'high' then → cellulose insulation breakdown (sup = 11%, conf = 50%)
5. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'high' and CO = 'high' then → cellulose insulation breakdown (sup = 11%, conf = 33%)
6. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'normal' and CO = 'high' then → cellulose insulation breakdown (sup = 14%, conf = 33%)
7. C_2H_2 = 'very high' and C_2H_6 = 'normal' and CH_4 = 'normal' and C_2H_4 = 'very high' and CO = 'high' then → cellulose insulation breakdown (sup = 11%, conf = 33%)

It is observed that more reasons are extracted by the addition rules of the above when compared to the Key Gases Rules. For example, in the Key Gases Method, corona is revealed by a high hydrogen concentration. However, the Apriori algorithm has identified some extra conditions or relations which might be caused by corona (rule 3).

With this analysis, a conclusion can be drawn. By using the data mining technique, some valid rules might be generated. However, the validity of the rules is highly dependent on the amount of data available. Thus, the quality of the rules generated in this experiment may not be in high validity due to the small number of previous data captured. However, with a larger collection of test data and corresponding fault types, data mining can actually produce rules of higher validity. Hence, this method may be applied in the future when more data is available.

5.5 Advantages and Disadvantages of the DM Technique

A number of advantages can be identified when using the DM technique to extract the rules, which can be summarized as follows:

- DM is able to unearth hidden significant correlation that has not been identified by the experts and, thus, help domain expert to search for previously unknown patterns of behaviour.
- The rule base can be continuously updated which reflects the content of the database.
- By generating a series of rules for different time range, engineers can observe the trend of the fault occurrence and some precautionary measures can be taken during future maintenance to avoid serious damage.
- Rule discovery is an automatic process and thus can reduce laborious tasks of coding rules and extracting from experts.
- DM manipulates the data to build an understandable model and in turn helps in saving cost in instead of paying foreign expertise.

However, there are several disadvantages in the DM technique:

- The rule generation procedure needs to be run repetitively in order to produce the most current model representation. This overhead is unavoidable for continuously updating the set of extracted rule is still an ongoing research in DM literature.

- The generation of a representative rules is highly dependent on the volume of samples for learning. Due to the lack of a large number of past records, some of the rules might not be significant (low confidence or support) and in turn will not be extracted.
- Bad data or invalid data may lead to the formation of wrong or invalid rules which can be detrimental to the systems.

5.6 Conclusion

In this chapter, an implementation of a DM algorithm to extract significant rules which describes the relationship between the fault type and the type of gases and their concentration dissolved in the oil is described. Through this technique, the fuzzy rule base’s can be improved in two ways. First, the expert defined rules can be proven or supported and secondly, a set of additional rules can be included into the rule base for better diagnosis of the transformer condition.

CHAPTER IV

SOFTWARE DEVELOPMENT

Proper functioning of power transformers is critical to secure operation of the power system. Thus, **A** Software for Intelligent **D**i**a**gnostic of **P**ower **T**ransformer (ADAPT) is developed in order to manage the huge volume of transformer information and to identify the transformer health conditions efficiently and accurately. This ADAPT 2.0 can run using internet and intranet. The software development phase for ADAPT can be divided into two parts which are database development and intelligent diagnostic engine development. For the former, database management software is developed with the functionality of storing thousands of transformer information records, with flexible searching feature and other useful facilities. The latter involves designing an intelligent diagnostic engine which uses the Total Intelligent Diagnostic Solution (TIDS) architecture to diagnose the condition of the power transformers. In this chapter, the software development phases of ADAPT will be discussed in detail which include phase one: the database development and phase two: the intelligent diagnostic engine development.

4.1 Introduction to ADAPT

ADAPT is developed using Visual Basic 6.0 as front-end (application), Web base application using asp vbscript, IIS (Internet Information Services) and Microsoft SQL Server 2000 as back-end (database) and it is a 32-bit windows based program which can be executed in Microsoft Windows 95 or higher. Table 4.1 summarizes the software development tools for ADAPT.

Table 4.1 : ADAPT software development tools

ADAPT	Programming Tools
Database	Microsoft SQL Server 2000
Software/Application	Microsoft Visual Basic 6.0, frontpage.
Report	Seagate Crystal Report Professional version 9
Server	Internet Information Services

In order to meet the needs of high edge IT trends which emphasizes on fast information retrieval and frequent access, this software is capable to be implemented either as a standalone or client-server basis which support multi-user access to the database concurrently. In order to used the ADAPT software as a client-server application, ADAPT needs to be located in a powerful server with at least a Pentium based CPU and 32MB memory. The database server needs to be connected with the client computers in a Local Area Network (LAN) either using UTP or Coaxial cable. Figure 4.1 shows the splash screen for the ADAPT software Version 2.0.

Figure 4.1 : Splash screen for ADAPT software

The enhanced version of ADAPT consists of ADAPT *V2 client server* which runs on a local area network and *ADAPT V2 Web Client* which runs on Intranet/Internet.

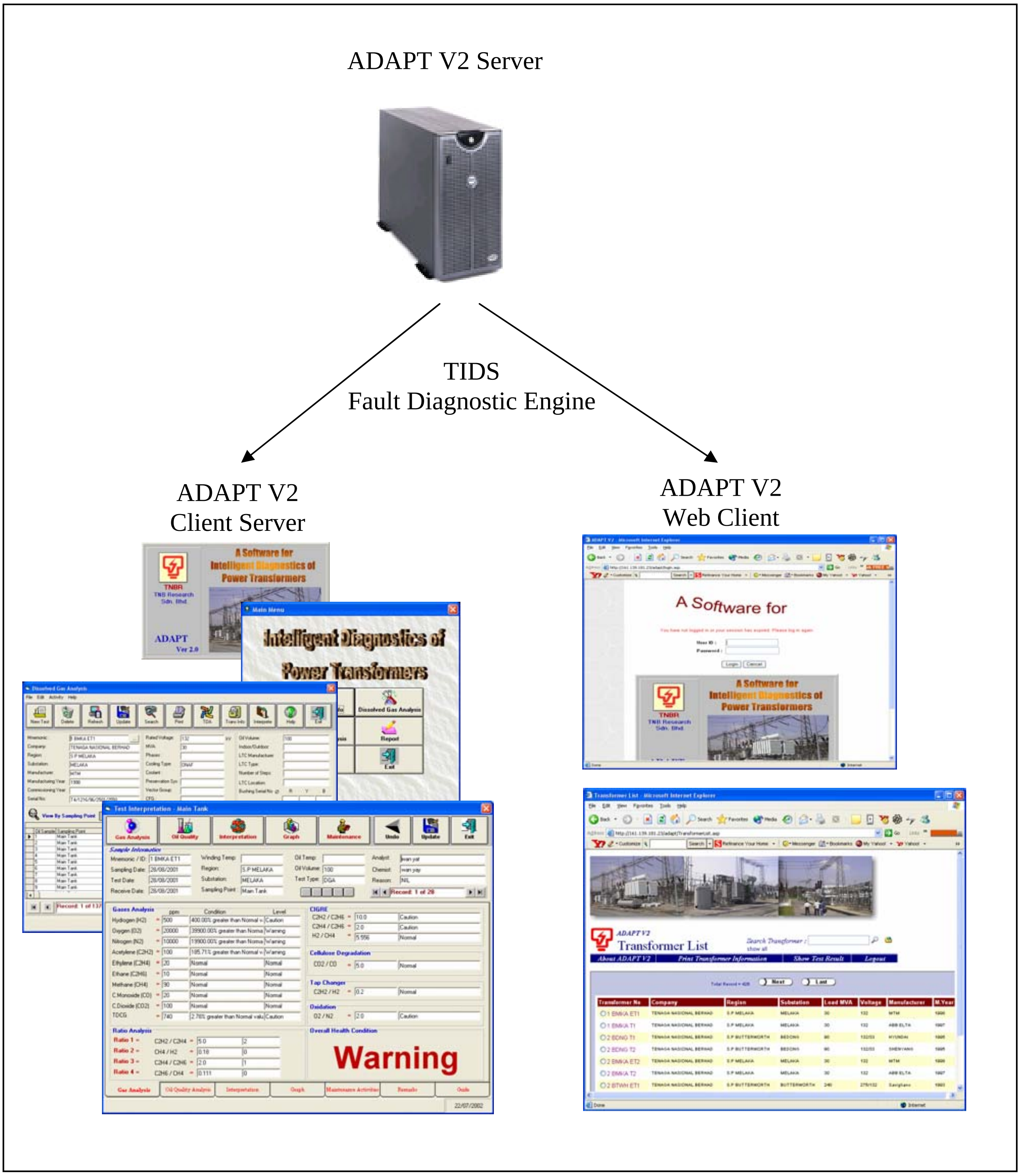


Figure 4.2 : Splash screen for ADAPT V2 web client software

The ADAPT software provides useful information to the TNB operator such as the transformer current health condition, the actions to be taken and the next recommended sampling date. In addition, this module also provides useful functions for the engineer to plot various graphs for each gas and generate different type of reports automatically. Previously, the report generating process is a time consuming task and usually takes few hours or a few days in order to retrieve the related transformer information manually before a standard report or graphs can be generated. These kinds of reports are important for the engineer to judge or predict the condition of the transformer. With the help of such system, the workload of the TNB engineers is greatly reduced and the condition of the power transformers can be monitored more closely to reduce the unwanted outage.

4.2 ADAPT Software Overview

The ADAPT software consists of 5 main modules as shown in Figure 4.2.

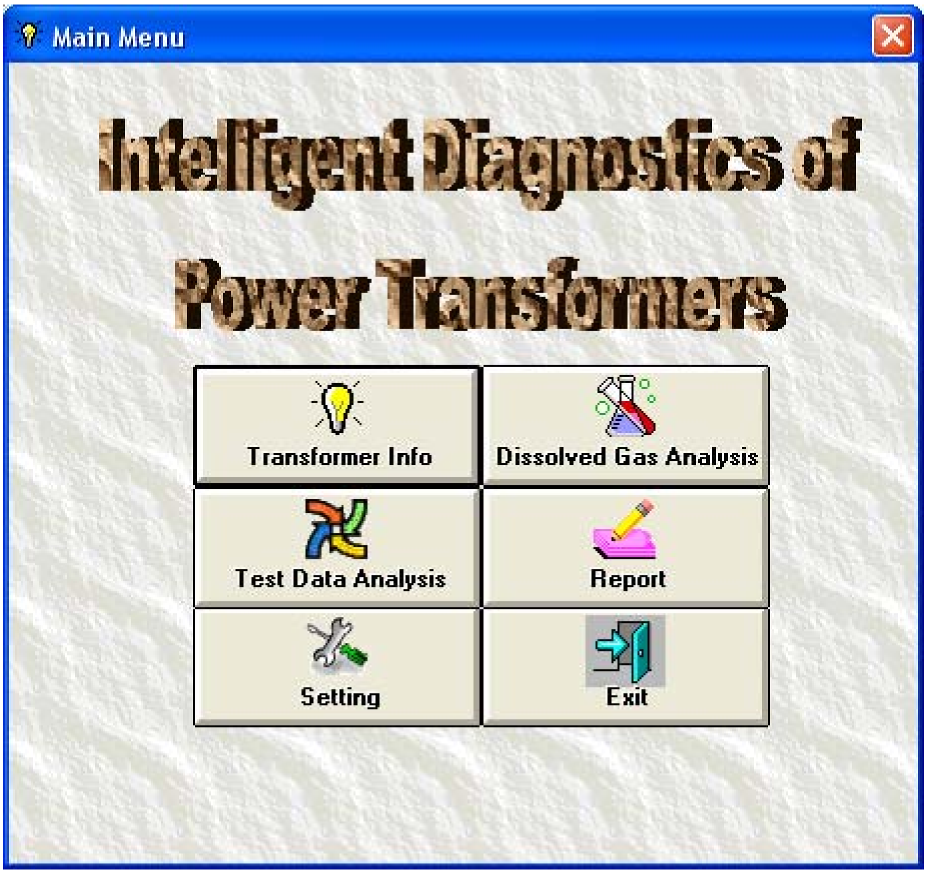


Figure 4.3 : Main modules of ADAPT

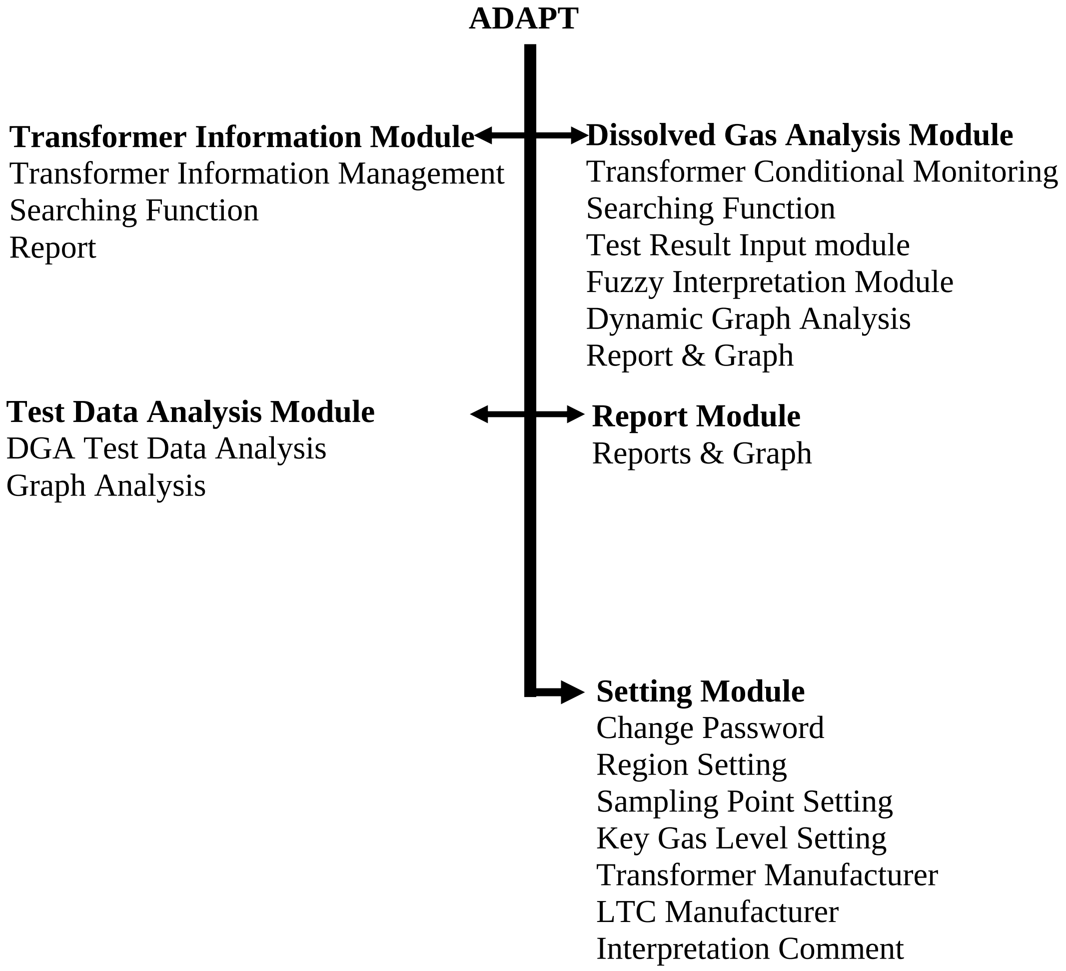
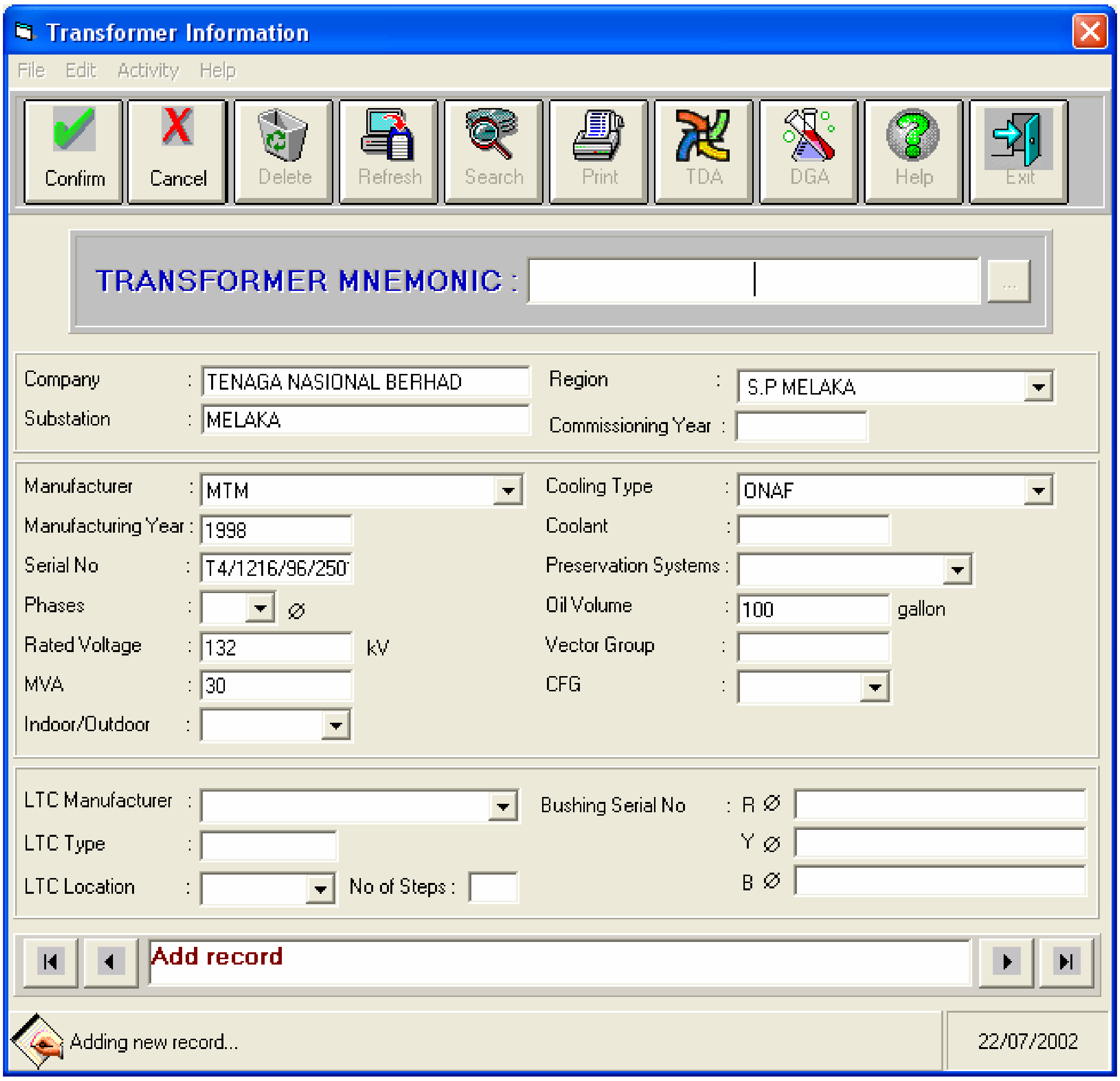


Figure 4.4 : ADAPT module summary

Figure 4.4 summarizes the detail information of the 5 modules in the ADAPT software. For this project, the intelligent diagnostic engine focuses on the DGA module with the fuzzy algorithm being integrated into the 4 main DGA diagnostic methods which forms the TIDS architecture.

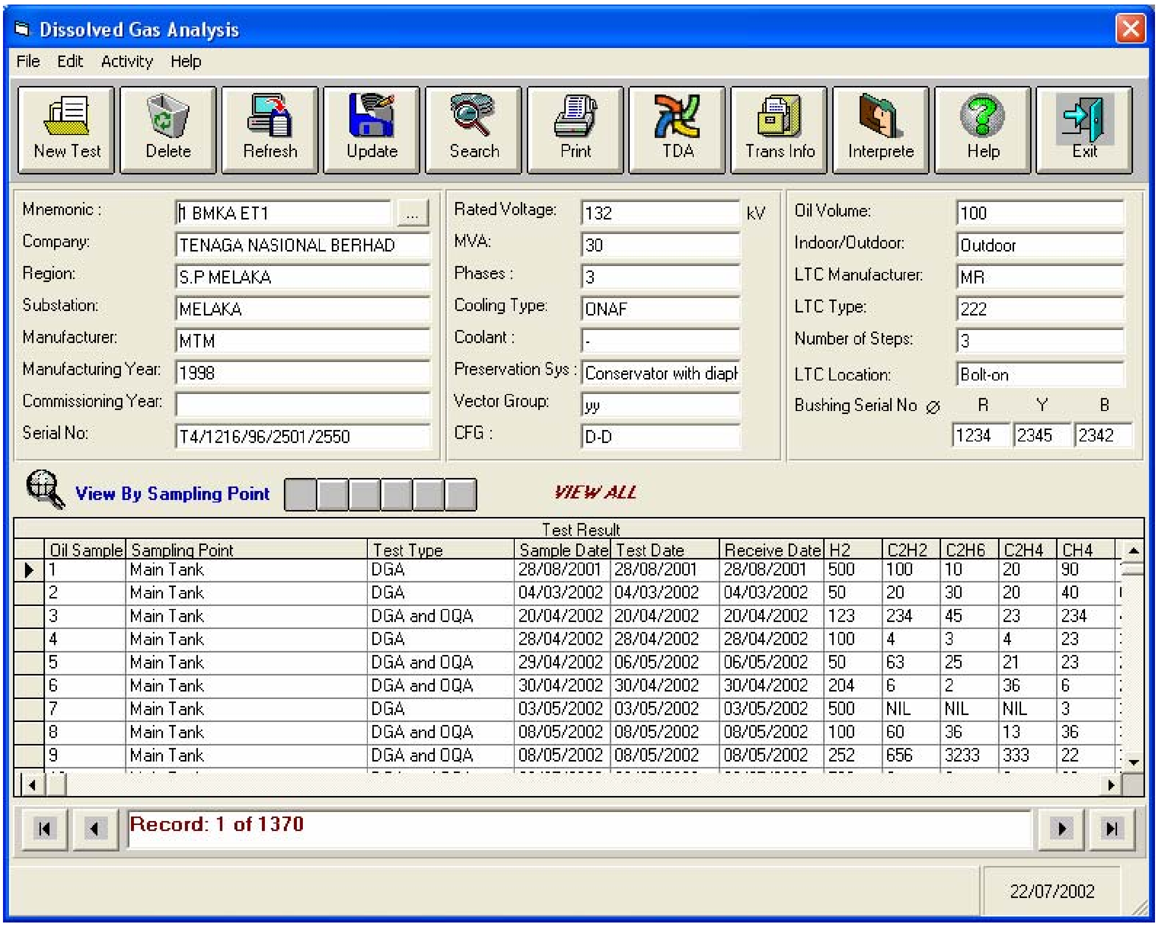
The Transformer Information Management module is a database management module which stores the necessary information of all the transformers in the country such as its make, year, location, ratings, etc.. From here the user can create new transformer records, retrieve existing records, update or delete certain transformer information. Moreover, the multi-criteria searching functions enable the user to group and analyze transformers of certain same features efficiently. For example, the transformers can be viewed or searched by region, substation, serial number or transformer mnemonic. Figure 4.5 illustrates the menu of the transformer information module.



Company : TENAGA NASIONAL BERHAD
Region : S.P MELAKA
Substation : MELAKA
Manufacturer : MTM
Cooling Type : ONAF
Manufacturing Year : 1998
Serial No : T4/1216/96/250
Oil Volume : 100 gallon
Rated Voltage : 132 kV
MVA : 30
Add record
Adding new record...
22/07/2002

Figure 4.5 : Main menu of transformer information module

The DGA module is meant for the engineer to keep the test results of each oil sample from various locations and sampling points as shown in Figure 4.6. After storing all the test results in the database, the software can interpret the test result based on the expert knowledge which resides in the ADAPT DGA module as shown in Figure 4.6.



Mnemonic : 1 BMKA ET1
Company: TENAGA NASIONAL BERHAD
Region: S.P MELAKA
Substation: MELAKA
Manufacturer: MTM
Manufacturing Year: 1998
Commissioning Year:
Serial No: T4/1216/96/2501/2550

Rated Voltage: 132 kV
MVA: 30
Phases : 3
Cooling Type: ONAF
Coolant : -
Preservation Sys : Conservator with diapl
Vector Group: yy
CFG : D-D

Oil Volume: 100
Indoor/Outdoor: Outdoor
LTC Manufacturer: MR
LTC Type: 222
Number of Steps: 3
LTC Location: Bolt-on
Bushing Serial No ⌀ R 1234 Y 2345 B 2342

Test Result

Oil Sample	Sampling Point	Test Type	Sample Date	Test Date	Receive Date	H2	C2H2	C2H6	C2H4	CH4
1	Main Tank	DGA	28/08/2001	28/08/2001	28/08/2001	500	100	10	20	90
2	Main Tank	DGA	04/03/2002	04/03/2002	04/03/2002	50	20	30	20	40
3	Main Tank	DGA and OQA	20/04/2002	20/04/2002	20/04/2002	123	234	45	23	234
4	Main Tank	DGA	28/04/2002	28/04/2002	28/04/2002	100	4	3	4	23
5	Main Tank	DGA and OQA	29/04/2002	06/05/2002	06/05/2002	50	63	25	21	23
6	Main Tank	DGA and OQA	30/04/2002	30/04/2002	30/04/2002	204	6	2	36	6
7	Main Tank	DGA	03/05/2002	03/05/2002	03/05/2002	500	NIL	NIL	NIL	3
8	Main Tank	DGA and OQA	08/05/2002	08/05/2002	08/05/2002	100	60	36	13	36
9	Main Tank	DGA and OQA	08/05/2002	08/05/2002	08/05/2002	252	656	3233	333	22

Record: 1 of 1370

22/07/2002

Figure 4.6 : The Dissolved Gas Analysis menu

Sample Information

Mnemonic / ID: 1 BMKA ET1
Sampling Date: 28/08/2001
Test Date: 28/08/2001
Receive Date: 28/08/2001
Winding Temp:
Region: S.P MELAKA
Substation: MELAKA
Sampling Point : Main Tank
Oil Temp:
Oil Volume: 100
Test Type: DGA
Analyst: wan yat
Chemist: wan yay
Reason: NIL
Record: 1 of 28

Gases Analysis

		ppm	Condition	Level
Hydrogen (H2)	=	500	400.00% greater than Normal v.	Caution
Oxygen (O2)	=	20000	39900.00% greater than Norma	Warning
Nitrogen (N2)	=	10000	19900.00% greater than Norma	Warning
Acetylene (C2H2)	=	100	185.71% greater than Normal v.	Warning
Ethylene (C2H4)	=	20	Normal	Normal
Ethane (C2H6)	=	10	Normal	Normal
Methane (CH4)	=	90	Normal	Normal
C.Monoxide (CO)	=	20	Normal	Normal
C.Dioxide (CO2)	=	100	Normal	Normal
TDCG	=	740	2.78% greater than Normal valu	Caution

CIGRE

C2H2 / C2H6	=	10.0	Caution
C2H4 / C2H6	=	2.0	Caution
H2 / CH4	=	5.556	Normal

Cellulose Degradation

CO2 / CO = 5.0 Normal

Tap Changer

C2H2 / H2 = 0.2 Normal

Oxidation

O2 / N2 = 2.0 Caution

Ratio Analysis

Ratio 1 =	C2H2 / C2H4	=	5.0	2
Ratio 2 =	CH4 / H2	=	0.18	0
Ratio 3 =	C2H4 / C2H6	=	2.0	1
Ratio 4 =	C2H6 / CH4	=	0.111	0

Overall Health Condition

Warning

22/07/2002

Figure 4.7 : Presentation of the fuzzy interpretation module

The Test Data Analysis Module is an analysis tool for helping the engineer to locate the list problematic transformers quickly. This tool allow the user to define their own set of criteria or parameter in order to locate the related information from the ADAPT database. For example, the user may need to know which transformer has the hydrogen concentration greater than 500 ppm. This can be done by entering the appropriate values in the designated boxes in the “Test Criteria” frame as shown in Figure 4.8. Furthermore, the user can find a list of faulty transformers by pressing the button “Overlimit” or “Critical” button. After clicking the “Overlimit” button, the system will fills up the parameter value for an unhealthy condition automatically and consequently users are required to press the “Search All” button to list out all the faulty transformer of this module. The parameter values set by the “Overlimit” button is based on the IEEE standard while the “Critical” button setting is based on the IEEE standard value with an increment of 10 percent. Figure 4.8 shows the menu for the test data analysis module.

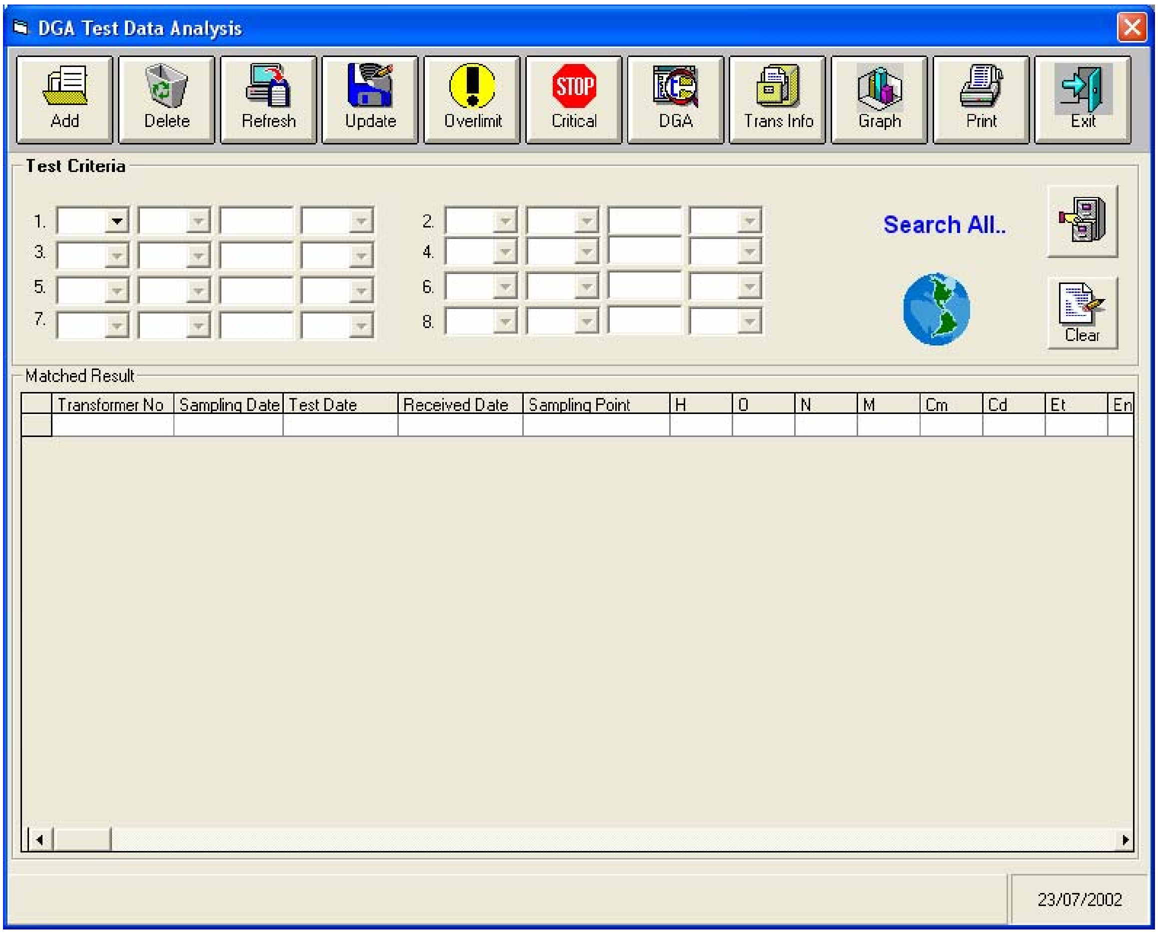


Figure 4.8 : Test data analysis module

For the report module, various type of report can be printed directly from here. There are a total of 30 reports and graphs specially designed for TNB as listed below and the sample of each report can be obtained in Appendix C.

i. Transformer information report (Transformer information module)
ii. Test result report for Transmission Department (DGA Module)
iii. Test result report for chemistry Department (DGA module)
iv. Graph for Hydrogen (DGA module)
v. Graph for Oxygen (DGA module)
vi. Graph for Nitrogen (DGA module)
vii. Graph for Methane (DGA module)
viii. Graph for Carbon Monoxide (DGA module)
ix. Graph for Carbon Dioxide (DGA module)

x. Graph for Ethylene (DGA module)
xi. Graph for Ethane (DGA module)
xii. Graph for Acetylene (DGA module)
xiii. Graph for Moisture (DGA module)
xiv. Graph for Acidity (DGA module)
xv. Graph for TDCG (DGA module)
xvi. Fuzzy Interpretation Report (DGA module)
xvii. Graph for all gases (DGA module)
xviii. List of overlimit transformers (Test data analysis module)

The ADAPT software provides flexible facility for the user to customize the setting of the software in the setting module as shown in Figure 4.9. This module is for the user to maintain the system settings or change the user password. There are seven functions in this module:

- Change user password or create new user account (Change Password)
- Add or edit the region for the transformer (Region)
- Add or edit the sampling points for the transformer (Sampling Point)
- Define the normal Key Gas Level
- Add or edit the transformer manufacturer information
- Add or edit the LTC Manufacturer information
- Add or edit the interpretation comment

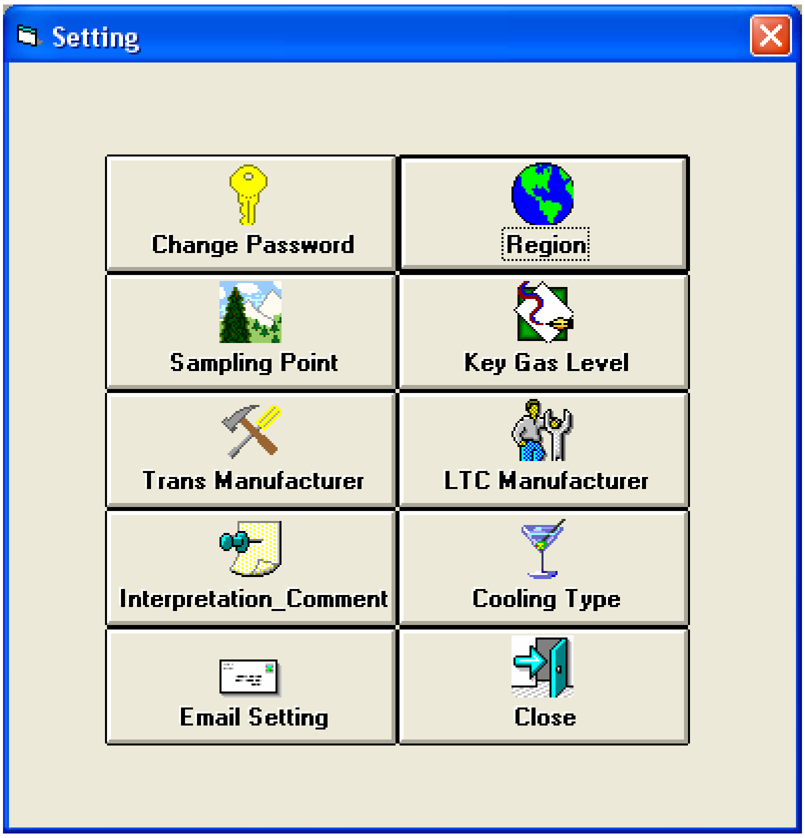


Figure 4.9 : ADAPT setting module

Figure 4.10 illustrates the functionality breakdown of ADAPT software in hierarchy chart. From the hierarchy chart, all the 5 main modules of ADAPT software are listed at the upper level while the functionality and features are listed at the bottom part of each modules.

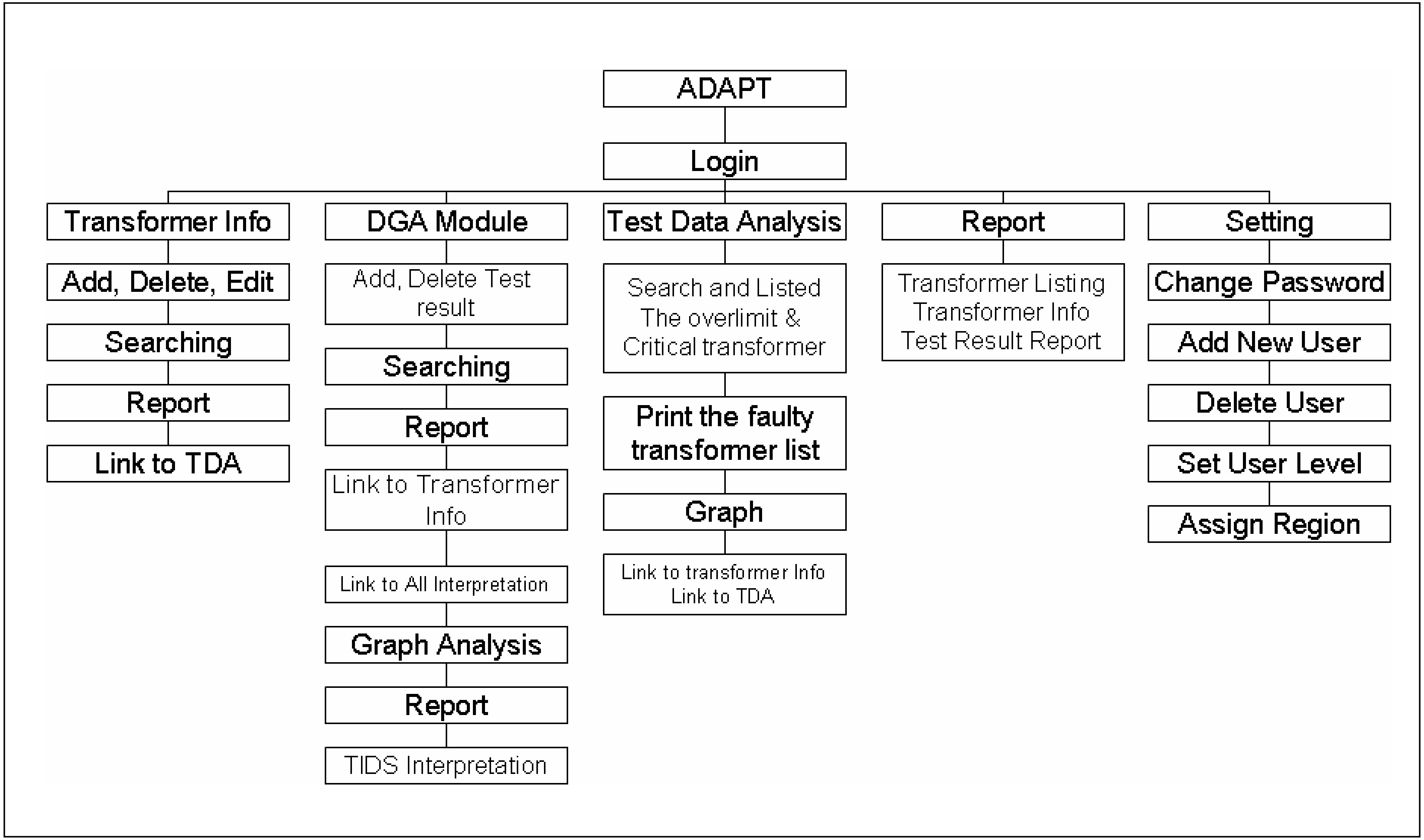


Figure 4.10 : Functionality breakdown of ADAPT 2.0 software

4.3 Software Design and Methodology

The ADAPT software development are divided into two phases. Phase one is to develop a client-server database management software for keeping all the transformer information and the DGA test result while phase two is focused mainly on the intelligent fault diagnostic engine where the TIDS architecture is being designed to interpret the DGA test result. Figure 4.11 summarizes the ADAPT software development phases.

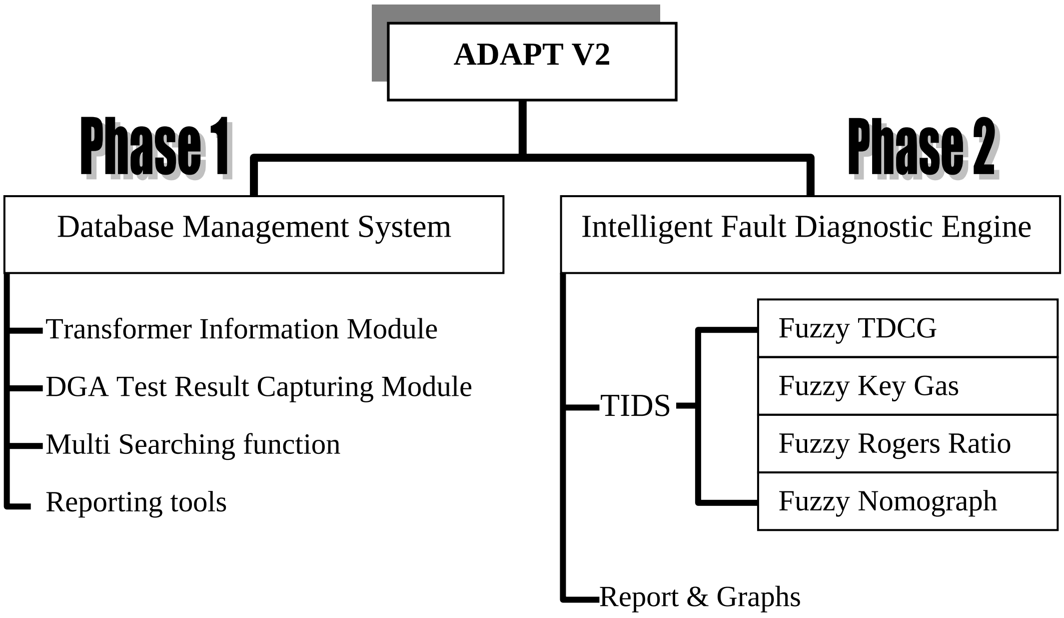


Figure 4.11 : ADAPT software development phases

4.3.1 Phase 1 – Database Development

The main purpose of developing the database software is to manage the transformer information systematically so that the information retrieval job can be done quickly and easily. Previously, when a new oil sample test result is submitted by a sub station, the engineer needs to search for the transformer record from a huge volume of file cabinet manually and key in the test result in Microsoft Excel format then print it out and store in the file cabinet again. These repetitive processes are time consuming and usually need a few people to handle such a large volume of data. In order to overcome this problem, a database management system is developed to manage the huge volume of data systematically. Besides organizing the data more efficiently, this database management system also helps to provide necessary data for intelligent analysis in the latter phase.

The ADAPT database is developed based on the standard software development model known as “waterfall model” or “software life cycle” (Sommerville, 1995). The waterfall model splits the software development process into 5 stages as illustrated in Figure 4.12.

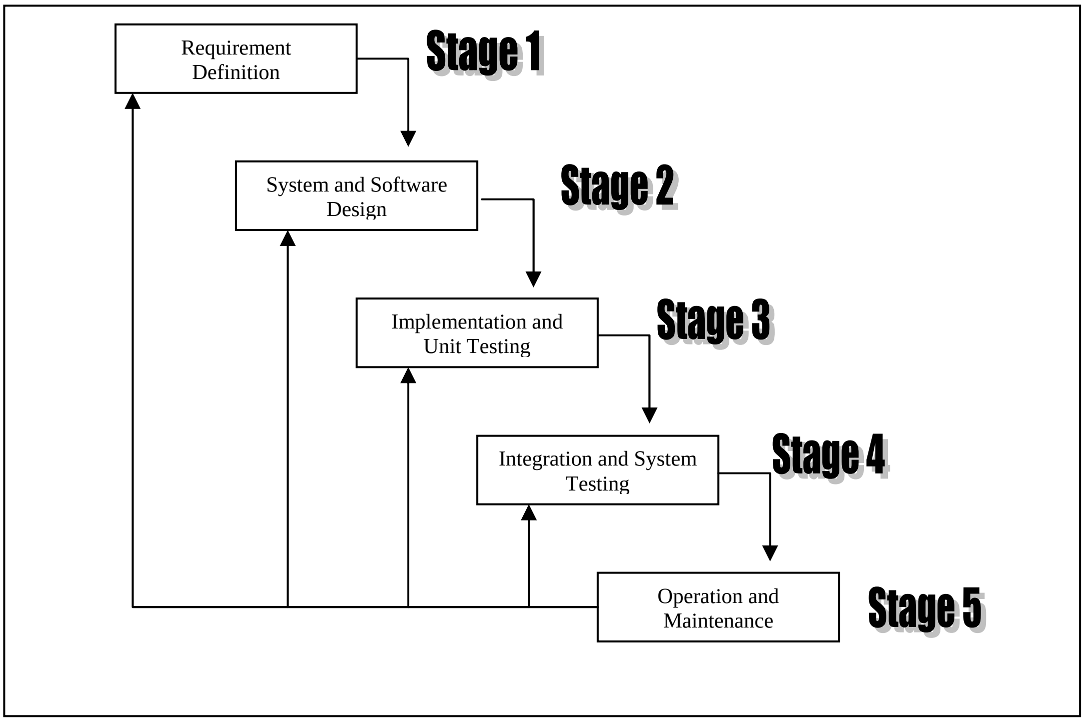


Figure 4.12 : Waterfall model

Because of the cascade structure from one phase to another, this model is known as the “waterfall model” and this model is now widely used for practical system development. The following text briefly described each stage of the waterfall approach in accordance to the ADAPT software development.

i. Requirement definition

This is a process of deriving the system requirement through observation of the existing system, discussion with TNB potential users and study the tasks need to be automated. In this stage, the system's services, constraints and goal are established through the consultation with TNB engineer and system user. The information gathered during the analysis activity are then translated into document which defines a set of requirements. These requirements are understandable and agreed by both users and development team.

ii. System and software design

The system design process partitions the requirement into different modules or sub-system and defined the relationship between each sub-system. There are a few tasks involve during this design stage which can be described as follows:

(a) Design the database structure of the software based on various forms and reports gathered such as the transformer record form and the test result report from the TNB. The entity relationship of each table is defined based on the information gathered from the system users.
(b) Design the system workflow and the graphical user interface (GUI) for the software.
(c) Design the software features such as searching function, adding function, updating and deleting function
(d) Design the report layouts and the graphs as requested by the TNB

iii. Implementation and unit testing

During this stage, the software design is realized as a set of programs or program units. All the modules defined in the software design stage is coded using Visual Basic 6 and for web client using asp vbscript while the database structure of the ADAPT software is constructed using Microsoft SQL Server 2000. Unit testing involves verifying that each unit meets its specification.

iv. Integration and system testing

The individual program units or programs for each module are integrated and tested as a complete system to ensure that the software requirements have been met.

v. Operation and maintenance

After testing, the ADAPT software is delivered and installed at the TNB site for practical use. Maintenance involves correcting errors which were not discovered in earlier stages of the life cycle, improving the implementation of the system units and enhancing the system services as new requirements are discovered at this stage. Normally, making changes to the system may involve repeating some or all previous process stages and this loop will keep on repeating in the maintenance stage whenever a new functionality is identified.

4.3.2 Phase 2 – Intelligent Fault Diagnostic Engine Development

In order to provide a complete and accurate prediction for the fault of the transformer, a Total Intelligent Diagnostic Solution (TIDS) is implemented as the ADAPT fault diagnostic engine. This engine utilizes 4 well-known DGA fault diagnostic methods which are incorporated with the fuzzy logic algorithm in order to provide human-like interpretation. In TIDS, the fault diagnostic methods are divided into two categories which are **Main Interpretation** and **Supportive Interpretation** as shown in Figure. 4.13.

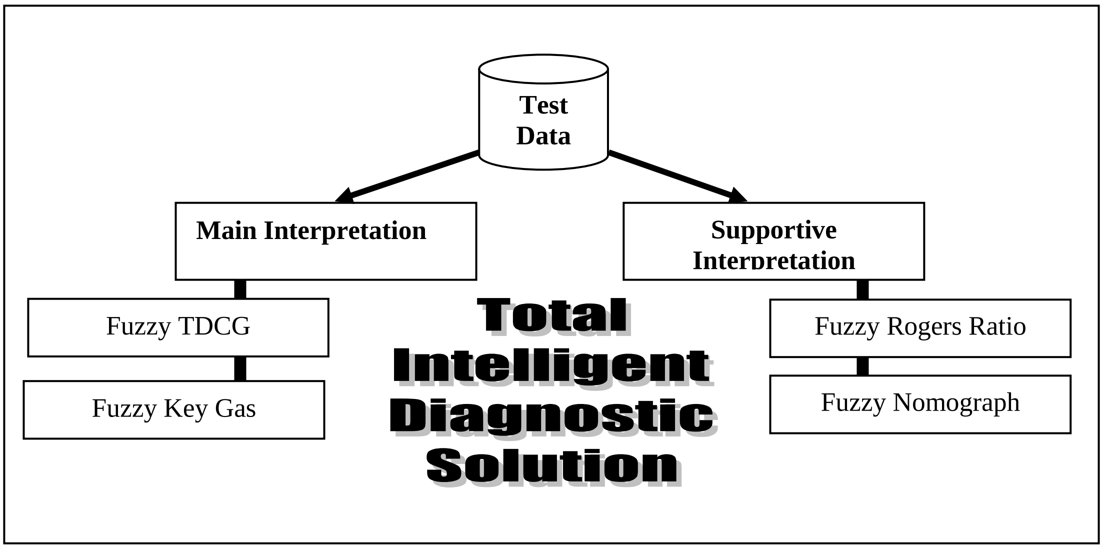


Figure 4.13 : TIDS architecture

The purpose of the main interpretation is to determine the transformer health condition, operating procedure and the next sampling interval while the supportive interpretation is proposed to ensure and verify the interpretation result generated by the main interpretation method. If there is any contradiction between the main interpretation and supportive interpretation, the main interpretation result will be considered significant. However, the system will prompt the user that a contradiction occurs and hence stimulate for human expert assistance. With this enforcement, the system will call for experts' advice to avoid unnecessary danger, especially when encountering with bizarre situations.

4.3.2.1 Main Interpretation

The main interpretation part consists of two DGA diagnostic methods which are Fuzzy TDCG and Fuzzy Key Gas methods. The former is responsible for determining the transformer operating procedure and predicting the next appropriate sampling interval while the latter is accountable for diagnosing abnormalities of transformer such as Thermal, Corona or Arcing problems. The detail information of the Fuzzy TDCG and Fuzzy Key Gas methods can be obtained from Chapter 3. In the main interpretation part, the interpretation results are ordered and categorized systematically into a few sections. The first section is the TDCG level summary where the current TDCG, previous TDCG, sampling duration, TDCG rate, TDCG gas in feet square (ft^3) and TCGv values are displayed. The TDCG gas in ft^3 and TCGv can be calculated by equation below:

$$\text{TDCG Gas in Ft}^3 = \frac{currentTDCG - previousTDCG \times OilVolume \times 10^{-6}}{7.5 \times TimeInDay} \qquad (4.1)$$

$$\text{TCGv} = \frac{currentTDCG \times OilVolume}{1000000} \qquad (4.2)$$

In Section 2, all the combustible fault gases that exceeded its normal value will be listed out in this section. The following section is meant for indicating the fluid quality where the moisture and acidity are the main components to determine the quality of the insulating oil. In the last section, the diagnosis summary based on Fuzzy Key Gas and the recommended action or advice will be given in the main interpretation. The sample of the main interpretation result can be shown in Figure 4.14.

```
<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG            = 1307 ppm
Previous TDCG           = 355 ppm
Sampling Duration       = 38 days
TDCG Rate               = 25.05 ppm/day
Gas In Ft3              = 0.02 ft3/day
TCGv                    = 7.42 ppm

Gases Over Limit Value:
Current H2              = 324 ppm
Previous H2             = 153 ppm

Current C2H2            = 575 ppm
Previous C2H2           = 117 ppm

Current C2H4            = 185 ppm
Previous C2H4           = 36 ppm

Fluid Quality:
Current  Moisture       = 35 ppm
Previous Moisture       = 25 ppm

Summary of Diagnosis:
Arcing - 100%
Corona/Partial Discharge - 100%
High Temperature Oil Breakdown - 100%
Oil Oxidation - 100%

Note:
- The Moisture/Acidity content is higher than the normal condition.
- The oil may need reclamation for further service.
- Oil seems to be oxidized and may be forming sludge which can deteriorate the heat transfer of oil
  and causing the transformer to operate at a high temperature.
- Check the power factor and dielectric strength of the oil.

Advices :
- Most encouragable operating procedure:-
  Exercise caution.
  Analyse for individual gases.
  Determine load dependence.

- Most encouragable oil resampling interval:-  Monthly
```

Figure 4.14: Example of a main interpretation result

4.3.2.2 Supportive Interpretation

For the supportive interpretation, the Fuzzy Rogers Ratio and Fuzzy Nomograph methods are used to diagnose the condition of the power transformer. This part provides more information on the transformer fault which can assist an experienced TNB user to make decisions related to the transformer fault interpretation. The supportive interpretation is essential as the main interpretation uses the Key Gas method that can detect only 5 common faults which are not sufficient. For example, the Key Gas method can successfully detect the fault of Corona/Partial Discharge while the Rogers Ratio method can detect more details information about the same fault type that can be detected by the Key Gas method as listed below:

i. Partial discharge of low energy density or hydrolysis
ii. Partial discharge of high energy density
iii. Coincidental partial discharge and conductor overheating
iv. Partial discharge of increasing energy density

Sometimes, when a fault occurs inside the transformer, the transformer maintenance engineers need to know detail information about the fault before they can take any precaution action. This problem can be solved by using the supportive interpretation result to assist them to understand the transformer condition in much detail before any action can be considered. The detail description of the Fuzzy Rogers Ratio and Fuzzy Nomograph can be obtained in Chapter 3. Figure 4.15 shows the interpretation result of the supportive interpretation.

Fuzzy Rogers Ratio Method:
The transformer is most probably in High Energy Discharge: Arc with Power Follow Through - 86.04%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : Arcing - 100%
The transformer is in critical condition of fault : Corona/Partial Discharge - 100%
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Oil Oxidation - 100%

Logarithmic Nomograph Method:
Highly Significant of fault Arcing

Figure 4.15: Example of a supportive interpretation result

4.4 Analysis: ADAPT Interpretation

The ADAPT software is developed specifically for TNB and will be used in all its 9 regions in Malaysia for keeping track and diagnosing the condition of the power transformers. Hence, the ADAPT software should meet the required specification by providing accurate interpretation which had been defined in the earlier stage of the development. In order to test the reliability of the ADAPT software, two case studies are carried out with the help from the TNB engineers to provide the test data and human expert interpretation.

4.4.1 Case Study 1

In this case study, three sets of test results taken from three transformers located in the TNB of Kuala Lumpur North and South regions are used to test the accuracy and reliability of the ADAPT software. All of these transformers have faults justified by TNB experts after a thorough analysis. In judging the condition of a transformer, the experts use their previous knowledge or experiences of transformer condition diagnosis to perform an analysis manually. However, due to the lack of local expertise in the field of transformer diagnosis, the test data are usually send to experts overseas which consequently cause the analysis task to be quite expensive and time consuming. To reduce the dependency of foreign labour, the ADAPT software is developed based on the knowledge of these experts, the standard fault diagnostic method and the fuzzy logic algorithm. In this case study, the ADAPT software will be used to give the interpretations based on the expert knowledge that has been extracted from the human experts and coded into the fuzzy rules base. The real test data provided by TNB is listed in Appendix D.

4.4.1.1 Objective

The objective of this case study is to compare the evaluation of an oil sample between an expert and ADAPT. From this case study, the reliability and validity of ADAPT can be proven.

4.4.1.2 Result

There are a total of 17 test data taken within Jan 1997 to Nov 1999 from three transformers located in KL South and KL North substation. All the test data are keyed into the ADAPT software and interpreted using the DGA module. For each test data listed in Appendix D, the ADAPT interpretation result are printed and attached together with the test data. From the observation, most of the ADAPT interpretation result are consistent with the human expert interpretation with an accuracy rate of 100%. There are 6 cases where the ADAPT interpretations did not match with the human interpretations, however, after a second verification by several TNB engineers, the ADAPT interpretations were found to be correct and accepted by the engineers. These contradictory cases are shown in Appendix D.

4.4.1.3 Conclusion

With the diagnostic result obtained from the ADAPT software, it is proven that the ADAPT software is as smart as the human expert in diagnosing the condition of the power transformers. This is because the application of fuzzy logic technique allows the ADAPT software to judge the faults severity in a more natural form which cannot be done using the ordinary fault diagnostic method. In addition, with the TIDS architecture which employed four DGA diagnostic methods, more information about the condition of the transformers are available which is important for the TNB maintenance team to maintain or repair the faulty transformers quickly.

4.4.2 Case Study II

A case study was carried out using the test records obtained from the transformer database. There are a few hundreds test records in the transformer database but only 100 complete test records were selected for this case study. The gases involved in this case study are Acetylene (C_2H_2), Hydrogen (H_2), Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4) and Carbon Monoxide (CO). The test data set and analysis are listed in Appendix E.

4.4.2.1 Objective

The purpose of this case study is to compare and verify the human expert interpretation result with the ordinary Rogers Ratio interpretation result and the Fuzzy Rogers Ratio interpretation result. Through this case study, the advantages of applying fuzzy logic in DGA method can be clearly shown by comparing the differences between ordinary Rogers Ratio interpretation results with the Fuzzy Rogers Ratio interpretation.

4.4.2.2 Result

In this case study, the result generated from ordinary Rogers Ratio method and Fuzzy Rogers Ratio are compared with the human interpretation in which we assume that all the results provided by the human expert is correct. Table 4.2 shows the comparison of ordinary Rogers Ratio result and Fuzzy Rogers Ratio result.

In this case study, both ordinary and Fuzzy Rogers Ratio has “no match” cases. This is because the Rogers Ratio table only employs 22 rules out of 72 rules to determine 15 conditions. When the ratio code falls outside the expected range, a “no match” case will happen. However, with the advantage of fuzzy logic algorithm, the no match cases can be reduced as much as 6 percent as shown in Table 5.2 where the matched cases for Rogers Ratio method is 63% while the matched cases for Fuzzy Rogers Ratio is 69%.

Table 4.2 : Comparison of ordinary Rogers Ratio and Fuzzy Rogers Ratio result

Rogers Ratio Method	**Fuzzy Rogers Ratio Method**
Total test record : 100 Matched cases **(A- P)** : 63 Unmatched case **(∅)** : 37 Correct case **(✓)** : 40 / 63 Wrong case **(×)** : 23 / 63 Percentage: Correct case **(✓)** : 63.5 % Wrong case **(×)** : 36.5 %	Total test record : 100 Matched cases **(A- P)**: 69 Unmatched case **(∅)** : 31 Correct case **(✓)** : 44 / 69 Wrong case **(×)** : 25 / 69 Percentage: Correct case **(✓)** : 63.8 % Wrong case **(×)** : 36.2 %

** Correct case - The result same as the human expert interpretation*

** Wrong case - The result different with the human expert interpretation*

4.4.2.3 Conclusion

This case study shows that the Fuzzy Rogers Ratio can get more matched cases (69) compared with the ordinary Rogers Ratio (63). This is because the ordinary Rogers Ratio uses the crisp set which allows only full membership or no membership at all whereas the Fuzzy Rogers Ratio allows partial membership.

In some situations, the Rogers Ratio method also interprets wrongly due to the ratio code generation. Table 4.2 shows there are about 36 percent of wrong cases. Example below shows 2 extreme cases which produce the same result.

Table 4.3: Test data

	C2H2	H2	C2H6	CH4	C2H4	CO	R1	R2	R3	R4	**result**	
Case I	84	20	5	12	36	209	1	0	2	0	**H**	✓
Case II	3	9	1	6	4	150	1	0	2	0	**H**	**x**

Case I

R1 = C2H2 / C2H4 = 84 / 36 = 2.3333 = 1

R2 = CH4 / H2 = 12 / 20 = 0.6 = 0

R3 = C2H4 / C2H6 = 36 / 5 = 7.2 = 2

R4 = C2H6 / CH4 = 5 /12 = 0.416 = 0

TDCG = 366 ppm

Case II

R1 = C2H2 / C2H4 = 3 / 4 = 0.75 = 1

R2 = CH4 / H2 = 6 / 9 = 0.66 = 0

R3 = C2H4 / C2H6 = 4 / 1 = 4 = 2

R4 = C2H6 / CH4 = 1 / 6 = 0.16 = 0

TDCG = 173 ppm

Case I shows a high level of concentration as compared to Case II. In this scenario, Case II is supposed to represent NORMAL conditions due to the low level of concentration on average. However, according to the ratio calculation, both cases produce the same ratio values and thus direct to the same fault type (H – Arcing) which clearly shows the Rogers Ratio limitation. In order to overcome this problem, the Total Dissolved Combustible Gas (TDCG) ranges need to be considered in diagnosing the transformer condition. TDCG is the total of all flammable gases in the oil sample, it consist of H2, C2H2, C2H4, C2H6, CH4 and CO. We can validate the Rogers Ratio result with the TDCG value, if the TDCG value is above the normal value then the Rogers Ratio interpretation is valid. Due to this, the TDCG and Fuzzy Key Gas are used as the main interpretation diagnostic method while the Fuzzy Rogers Ratio method and Nomograph method are used as the supportive interpretation in the TIDS architecture.

4.5 Conclusion

The ADAPT 2.0 software is developed using advance software development tools which emphases on user-friendly graphical user interface design, client server accessible and easy reports generation. In addition, the ADAPT software is equipped with a robust intelligent fault diagnostic engine which incorporates four well known DGA diagnostic methods to form the TIDS architecture. Thus, ADAPT can provide an accurate interpretation in any situation as early as possible to ensure that all the power transformers are maintained properly and therefore increase their lifetime.

CHAPTER VI

CONCLUSION

6.1 Overall Project Summary

In this project, a comparatively new intelligent diagnosis tool for power transformers which we called ADAPT has been developed at CAIRO of UTM. This software which consists of four established diagnostic methods makes it a unique solution for transformer fault prediction. In view that the initial diagnostic methods have their own weaknesses and limitations, incorporating these methods with fuzzy logic and combining them to produce an integrated solution has lead to a better and more reliable solution. The final solution is obtained based on four diagnosis evaluation methods and, hence, is more reliable than the results obtained from many other single evaluation method. Two case studies have proven the consistency between the software decision and the expert evaluation decision. In addition, the advantages of fuzzy logic can be clearly seen in solving boundary problems. Currently, the ADAPT software has been installed and used at the TNB main office in Kajang and will be distributed to all the 9 regions soon. The contribution of this project as seen in ADAPT can be summarized as follows:-

i. Design of a robust intelligent fault diagnostic architecture

A Total Intelligent Diagnostic Solution (TIDS) is constructed based on the four most widely used DGA diagnostic methods and the fuzzy logic algorithm. This new architecture can diagnose a wider range of transformer fault types and can provide more detail information about the transformer condition. With such valuable information, the TNB maintenance teams can act promptly in maintaining or repairing the faulty transformers in order to avoid any electricity interruption.

ii. Automating the DGA process

The DGA processes which are previously done manually and locally at many TNB regional offices are now more organized using a sophisticated client-server database system in this project. The database system allows fast record storing, record retrieving, test data analysis as well as the capability to perform intelligent interpretation. This helps to reduce the workload of TNB staff and increase the efficiency of the DGA interpretation process as well as the staff in TNB.

iii. Improve skills of local expertise

Malaysia's economy is shifting from production to knowledge economy (k-economy) which requires a lot of knowledge workers in the field of information technology, artificial intelligence, electronic commerce, etc. By developing an AI software product using the local resources and expertise to solve Malaysia's industrial problem such as this does help to improve the skills of local expertise and hence implementing k-economy strategy.

iv. Cost saving

Poor maintenance of power transformers may not only cause heavy losses but also a danger to human lives. A chain effect will occur such that a faulty power transformer may cause disruption of manufacturing production, transportation, household activities, etc. With the implementation of the ADAPT software to diagnose the conditions of the transformers, less faults in transformers may happen. In addition, by using the ADAPT software, the down-time and repair cost can be optimized and at the same time reducing the cost of foreign consultants which can cause the outflow of Ringgit.

v. Through discussion with electricity utility companies overseas, the ADAPT software is also one of very few such software available in the world. The software can actually be sold to many utility companies which can increase revenue for TNB and CAIRO.

6.2 The Benefits of ADAPT

As ADAPT is still new, its actual benefits can only be measured from savings the maintenance costs of power transformers at TNB. However, the immediate impacts of ADAPT can be summarized as follows:

i. Use of advanced technology and local expertise within Malaysia for solving complex industrial problems.

ii. Increased efficiency and reduced operational costs for power transformer maintenance.

iii. Time saving by organizing data systematically and automating calculations and reports.

iv. Early detection of abnormalities helps prevent unscheduled outages, equipment damage and safety hazards.

v. Cost savings since fewer personnel are needed for data entering and report writing.

Future impacts can be expected as follows:

i. Savings of outflow of Ringgit with less dependency on foreign consultants and expertise. This factor is important as previously TNB relies a lot on foreign experts in solving the complex industry problems which are highly expensive. With ADAPT, the cost of employing foreign consultants is reduced and thus may eliminate the outflow of Ringgit.

ii. Increased expertise of local consultant and in-house expertise. This is because the ADAPT software is developed totally locally by CAIRO and TNB engineers, thus leads to increased local expertise.

REFERENCES

1. Agrawal, R. and Srikant, R. (1994). “Fast Algorithms for Mining Association Rules.” Proc. of the 20th International Conference on Very Large Database. Santiago, Chile.

2. Bellon, C., Bosc, P. and Prade, H. (1992). “Fuzzy Boom in Japan.” *International Journal of Intelligent Systems.* **Vol. 7**. Pgs. 293-316.

3. Bengtsson, C. (1996). “Status and Trends in Transformer Monitoring.” *IEEE Transaction on Power Delivery*. **Vol. 11. No. 3.**

4. Bielawski, Larry and Lewand, Robert (1988). “Expert Systems Development Building PC-Based Applications.” Wellesley: OED Information Sciences, Inc..

5. Bonissone, P.P., Badami, V. et al. (1995). “Industrial Applications of Fuzzy Logic at General Electric.” Proc. of the IEEE. **Vol. 83. No. 3.** Pgs. 450-465.

6. British Standards Institution (1979). “Guide for the Interpretation of the Analysis of Gases in Transformers and other Oil-filled Electrical Equipment in Service.” London: (BS 5800).

7. Church, J.O. , Haupert, T.J. and Jakob, Fredi (1987). “Analyze Incipient Faults with Dissolved-gas Nomograph.” *Elecrical World*. Oct. Pgs. 40-44.

8. DiGiorgio, Joseph B. (1997). “Dissolved Gas Analysis of Mineral Oil Insulating Fluids.” California: Northern Technology & Testing.

9. Domun, M.K. (1996). “Condition Monitoring of Power Transformers by Oil Analysis Techniques.” Proc. of the 11th Conference on Electric Power Supply Industry (CEPSI). Kuala Lumpur, Malaysia.

10. Dorf, Richard C. (Ed.) (1996). “The Engineering Handbook.” United States: CRC Press, Inc.

11. Dukarm, James J. (1993). “Transformer Oil Diagnosis Using Fuzzy Logic and Neural Networks.” Canadian Conference on Electrical and Computer Engineering. Canada.

12. Esp, D.G., Carrillo,M. and McGrail, A.J. (1998). “Data Mining Applied to Transformer Oil Analysis Data.” Conference Record of the 1998 IEEE International Symposium on Electrical Insulation. Arlington, Virginia, USA

13. Fayyad, U.M., Piatetsky-Shapiro, G. and Smyth, P. (1996). “From Data Mining to Knowledge Discovery: An Overview.” *In Advances in Knowledge Discovery and Data Mining*. Cambridge, Mass: AAAI/MIT Press. Pgs. 1-34.

14. Flanagan, William M. (1993). “Handbook of Transformer Design & Application.” New York: McGraw-Hill, Inc.

15. Halstead, W.D. (1970). “Transformer Fault Diagnosis by Oil Decomposition Product Analysis.” Leatherland

16. Holmes, G., Cunningham, S. J. (1993), "Using Data Mining to Support the Construction and Maintenance of Expert Systems." New Zealand International Two Stream Conference on Artificial Neural Networks and Expert Systems. New Zealand: IEEE Computer Society Press. Pgs. 156-159.

17. Huang, Yann Chang, Yang, Hong Tzer and Huang, Ching Lien (1997). “Developing a New Transformer Fault Diagnosis System through Evolutionary Fuzzy Logic.” *IEEE Transaction on Power Delivery.* **Vol. 12. No. 2**.

18. Hyundai Heavy Industries Co., Ltd. (1993). “Installation, Operation and Maintenance Instruction for Power Transformer.” Ulsan Korea: A9508058-50484.

19. IEEE Standard (1992). “IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers.” New York: (C57.104-1991).

20. Kandel, Abraham (1992). “Fuzzy Expert Systems.” United States: CRC Press, Inc.

21. Lee, C.C. (1990). “Fuzzy Logic in Control System: Fuzzy Logic Controller – Part I & II.” *IEEE Transaction on Systems, Man and Cybernetics.* **Vol. 20. No. 2.**

22. Lin, C.E., Ling, J.M. and Huang, C.L. (1993). “An Expert System for Transformer Fault Diagnosis Using Dissolved Gas Analysis.” *IEEE Transaction on Power Delivery.* **Vol. 8. No. 1.**

23. Madan, S., Son, Won-Kuk and Bollinger, K.E. (1997). “Application of Data Mining For Power Systems.” IEEE Canadian Conference on Electrical and Computer Engineering.

24. Marzuki Khalid (1999). "Fuzzy Logic Control." UTM : Lecture Notes (unpublished).

25. Mamdani, E. H. (1993). “ Fuzzy Control in Japan: Learning Lessons.” *IEEE Colloqim on Two Decades of Fuzzy Control - Part I.* London.

26. Nogami, Takeki, et.al (1994). “Gas Discrimination Method for Detecting Transformer Faults by Neural Network.” IEEE International Conference on Neural Networks.

27. Quinlan, J.R. (Ed) (1987). “Applications of Expert Systems.” Sydney: Addison-Wesley Publishing Company.

28. Sommerville, Lan (1995). “Software Engineering.” England : Addison-Wesley.

29. Sorsa, Timo, Koivo, Heikki N. and Koivisto, Hannu (1991). “Neural Networks in Process Fault Diagnosis.” *IEEE Transactions on Systems, Man, and Cybernetics.* **Vol. 21. No.4.**

30. Sin Chew Jit Poh, 13 March 2000. “Explosion at TNB substation.”

31. Tan, Kok Khiang (1996). “Fuzzy Reasoning By Ordinal Structure Model for Elevator Group Supervisory Control.” University of Technology Malaysia: Master Thesis.

32. The Star, 13 March 2000. “Explosion at TNB substation.”

33. Tomdovic, Kelvin, Tapper, Matz and Ingvarsson, Tord (1993). “A Fuzzy Information Approach to Integration Different Transformer Diagnostic Methods.” *IEEE Transaction on Power Delivery.* **Vol. 8. No. 3.**

34. Wan, Yat How and Marzuki Khalid (1999). “Transformer Fault Diagnosis Using Fuzzy Logic Interpretations.” Conference Proceeding of InstrumentAsia99 (CIA99) Technical Symposium. Singapore.

35. Wan, Yat How and Marzuki Khalid (2000). “ADAPT - An Intelligent Software for the Diagnosis of Power Transformers.” Conference on Intelligent Solutions for Manufacturing Systems in the New Millennium. Kuala Lumpur, Malaysia.

36. Xu,W. et al.(1997). “Fault Diagnosis of Power Transformers : Application of Fuzzy Set Theory, Expert Systems and Artificial Neural Networks.” *IEE Proc.-Sci. Meas. Technol.* **Vol. 144. No. 1.**

37. Yan, Jun, Ryan, Micheal and Power, James (1994). “Using Fuzzy Logic.” New York: Prentice Hall International (UK) limited.

38. Yu, Philip S. (1999). “Data Mining and Personalization Technologies.” IEEE 6th International Conference on Database Systems for Advanced Applications (DASFAA '99).

39. Zadeh, L.A.(1965). “Fuzzy Sets.*”* *Information & Control*, **Vol. 8.** Pgs. 338-353.

40. Zhang,Y., Ding,X. and Liu,Y. (1996). “An Artificial Neural Network Approach to Transformer Fault Diagnosis.” *IEEE Transactions on Power Delivery*. **Vol. 11. No. 4.**

41. Zimmermann, H. J. (1986). “Fuzzy Sets, Decision Making, and Expert Systems.” Boston: Kluwer Academic Publishers.

APPENDIX A

LIST OF MNEMONICS OF THE POWER TRANSFORMERS IN MALAYSIA

S.P BUTTERWORTH

ASTR T1	ASTR T2	BBRU T1	BBRU T2
BBRU T3	BDNG SGT1	BDNG SGT2	BDNG T1
BDNG T2	BDRU T1	BDRU T2	BKTR T2
BLIN A	BLIN T1	BLIN T2	BLPS SGT1
BLPS SGT2	BLPS SGT3	BLPS T1	BLPS T2
BLPS T3	BLPS T4	BMJM ET1	BMJM ET3
BMJM ET4	BMJM T1	BMJM T2	BMJM T3
BMJM T4	BMTJ T1	BSIA T1	BSIA T2
BTBN ET2	BTBN SGT1	BTBN SGT2	BTBN T2
BTGH SGT1	BTGH SGT2	BTGH SGT3	BTGH T1
BTGH T2	BWTN T1	BWTN T2	BWTN T5
CPNG R1	CPNG SGT1	CPNG SGT2	FLIM T1
FLIM T2	FLIM T3	FLIM T4	GCPD T1
GCPD T2	GGOR T1	GGOR T2	GGOR T2A
GRUN T1	GRUN T2	JENG ET1	JENG T2
KCMT T1	KGAR T1	KGAR T2	KHTC ETR1
KHTC ETR2	KHTC T1	KHTC T2	KHTC T3
KHTC T4	KKTL T1	KKTL T2	KKTL T3
KKTL T4	KLIM ET1	KLIM ET2	KLIM T1
KLIM T2	KPLS T1	KPLS T2	KSTR SGT1
KSTR SGT2	KSTR T1	KSTR T2	KSTR T3
KSTR T4	PAUH T1	PAUH T2	PAUH T3
PAUH T4	PENG T1	PENG T2	PRAI ET1B
PRAI SGT1	PRAI SGT2	PRAI SGT3	PRAI T1
PRAI T1B	PRAI T2	PRAI T3	PRAI T4
PRID ET1	PRID ET2	PRID T1	PRID T2
PRID T3	PRID T4	PRIE T1	PWGR T1
PWGR T2	SPG4 T1	SPG4 T2	SPID T1
SPID T3	SPTN T1	SPTN T2	TBTU T1
TEWA T1	TEWA T2	TGPH T1	TGPH T2

TKBU ET1	TKBU ET2	TKBU T1	TKBU T2
TMBK T2	TMTN T7	UMKA ET2	UMKA T1
UMKA T2	UMKA T3	UMKA T4	VDOR T1
VDOR T2			

S.P IPOH

AMJA T1	APMC T1	BGJH T1	BSPT T1
BSPT T2	BSRI T1	BSRI T2	CEND T1
CENT T2	CIMA T1	GPRD T1	GPRD T2
HMTG T1	HMTG T2	JOR1	KGJ6 T1
KGJH T1	KGJH T2	KHAN T1	KHAN T2
KHAN T3	KJWA T1	KJWA T2	KKSR SGT1
KKSR SGT2	KKSR T1	KKSR T2	KMTG T1
KMTG T2	KNRG T1	KNRG T2	LMUT T1
LMUT T2	LPIA T1	LPIA T2	MGLB T1
MGLB T2	MNWR T1	MNWR T2	MNWR T3
NKAN T1	PAPN SGT1	PAPN SGT2	PAPN SGT3
PAPN T1	PAPN T1A	PAPN T1B	PAPN T2
PAPN T2A	PAPN T2B	PAPN T3	PAPN T4
PBTR T1	PBTR T2	PCAR T1	PCAR T2
PHCT T1	PKCB T1	PRAH T1	PRAH T2
SGRI T1	SIHY T1	SIHY T2	SLVR T1
SLVR T2	SPIA T1	SPNG T1	SSP6 T1
SSPT T1	SYPS T1	TASK T1	TASK T2
TASK T3	TINT T1	TINT T2	TINT T3
TMOH T1	TMOH T2	TMOH TT1	TPID T1
TPID T2	TPNG T1	TPNG T2	TSEK T1
TSEK T2	TSEK T3	TSEK T4	UPIA T1

S.P JOHOR BAHRU

ATWR T1	AWTR T2	BKTR T1	CHBU SGT1
CHBU T1	CHBU T2	DSRU T1	DSRU T2
KPTR T1	KPTR T2	KTGI T1	KTGI T2
KTGI T3	KTGI T4	MAJD T1	MAJD T2
PGDT T1	PGDT T2	PGIE T1	PGIE T2
PGPS T1	PGPS T2	PNAS T1	PNAS T2
PNWR T1	PNWR T2	PONT T1	PONT T2
PRJA T1	PRJA T2	PSAK T1	PSAK T2
RNGT T1	RNGT T2	SDAI SGT1	SDAI SGT2
SDAI T1	SDAI T2	SDAI T7	SDAI T8
SGM2 T1	SIPG SGT1	SIPG SGT2	SIPG SGT5
SIPG SGT6	SIPG T1	SIPG T2	SNAI T1
SNAI T2	STUL T1	STUL T2	TBRU T1

TBRU T2	TGLS T1	TGLS T2	TPOI T1
TPOI T2	TRMN T1	TRMN T2	YPGN T1
YPGN T2			

S.P KLUANG

AMPG T1A	BPHT T1	BPHT T2	BPHT T3
BPHT T4	JTGH T1	KLAI T1	KLAI T2
KLU1 T1	KLU1 T2	KLU1 T3	KLU1 T4
KLU2 T2	KLU2 T3	KLU2 T4	KLUG T1
KLUG T2	KLUG T3	KLUG T4	MUA2 T1
MUA2 T2	PLTG SGT1	PLTG SGT2	PSLG T1
PSLG T2	YGPG T1	YGPG T2	

S.P KUALA LUMPUR

AHTM T1	AHTM T2	AMPG T1B	AMPG T2A
AMPG T2B	ASMB T1	ASTM T1	BBDG T1
BBDG T2	BKJL T1	BKJL T2	BKJL T3
BKJL T4	BKPG T1	BKPG T2	BLKG T1
BLKG T2	BLKG T3	BLKG T4	BMKM T1
BMKM T2	BNTA T1	BNTA T2	BNTG T1
BNTG T2	BRAJ ET3	BRAJ T2	BRAJ T3
BRAJ T4	BTAI T1	BTAI T2	BTGA T1
BTGA T2	BTIN T1	BTIN T2	BTRZ ET3
BTRZ ET4	BTRZ T1	BTRZ T2	BTRZ T3
BTRZ T4	CBPS SGT1	CBPS SGT2	CBPS SGT3
CBPS T1	CBPS T2	CBPS T3	CBPS T4
CBTS T1	CBTS T2	CBTS T3	CBTS T4
DDSA ET1	DDSA ET2	DDSA T1	DDSA T2
DDSA T4	DGWI T1	DGWI T2	DMHT T1
DMHT T2	DMHT T3	DMHT T4	GCPK T1
GHLD T1	GHLD T2	GNTG T1	GNTG T2
GTNG T1	GTNG T2	GWAY SGT1	GWAY SGT2
GWAY SGT3	GWAY T1	GWAY T2	HCOM AT1
HCOM AT2	HCOM T1	HCOM T2	HCOM T3
HCOM T4	IGBK T1	IGBK T2	IGBK T3
IGBK T4	INTN T1	INTN T2	JENG T1
KCPK T1	KCPK T2	KKLW ET1	KLCC ET3
KLCC ET4	KLCC T1	KLCC T2	KLCC T3
KLCC T4	KLCCT3	KLIP T1	KLIP T2
KLJT T1	KLJT T2	KLJT T3	KLJT T4
KPNG T1	KPNG T2	KRAK T1	KSGR T1
KSGR T2	KTRI T1	KTRI T2	KULE SGT1
KULE SGT2	KULE SGT3	KULE T1	KULE T2

KULN AT1	KULN RCT1	KULN SGT1	KULN SGT2
KULN SGT3	KULN SGT4	KULN T1	KULN T2
KULN T3	KULN T4	KULS SGT1	KULS SGT2
KULS SGT3	KULS SGT4	KULS T1A	KULS T1B
KULS T2	KULS T2A	KULS T2B	KULS T3
KULS T4	MERU T1	MERU T2	MERU T4
NKST T1	NKST T2	NSEP T1	NSEP T2
NSEP T3	NSEP T4	ONST T1	PCHJ T1
PCHJ T2	PIDH ET1	PIDH T1	PIDH T2
PIDH T3	PIDH T4	PKLG SGT1	PKLG SGT2
PKLG SGT3	PKLG T1	PKLG T2	PKLG TR1
PKLG TR2	PMJU ET3	PMJU ET4	PMJU T1
PMJU T2	PMJU T3	PMJU T4	PROT T1
PROT T2	PTEK T1	PUBW T1	PULU SGT1
PULU SGT2	PULU SGT3	PULU T1	PULU T2
RAUB T1	RAUB T2	RAWG ET1	RAWG T1
RAWG T2	RAWG T3	RSID T1	RSID T2
SDAM T1	SDAM T2	SDAO T1	SDCA T1
SDCA T2	SEAP IBT1	SEAP IBT2	SEAP T1
SEAP T2	SEAP T2A	SEAP T3A	SEAP T3B
SGAD T1	SGBT ET1	SGBT ET2	SGBT T1
SGBT T2	SGDG T1	SHAB T1	SHAB T2
SHAN TA	SHAN TB	SHAS	SHAS T1
SHAS T2	SHAS T3	SHEL T1	SJSS T1
SMNK T1	SRON T1	SUDA T1	SUDA T2
TNBH T1	TNHQ T1	TNHQ T2	TPGR T1
TPGR T2	TTWS T1	TWSA T1	TWSA T2

S.P KUANTAN

AMCO T1	BIMK T1	BIMK T2	BMSH T1
BMSH T2	DGUN T1	DGUN T2	GBDK T1
GBDK T2	JNKA T1	JNKA T2	JNKA T3
JTUT T1	KAWA ET1	KAWA ET2	KAWA ET3
KAWA ET4	KAWA SGT1	KAWA SGT2	KAWA SGT3
KAWA SGT4	KAWA T1	KAWA T2	KMAN T1
KRYG T1	KRYG T2	KTAN T1	KTAN T2
KTGU T1	KTGU T2	KTNN T2	KTNN SGT1
KTNN T1	MECC T7	MRAN T1	MRAN T2
MSNG T1	MSNG T2	MTBE T1	MTBE T2
MTKB T1	PAKA SGT1	PAKA SGT2	PAKA SGT3
PAKA SGT4	PAKA T1	PAKA T2	PAKA T3
PAKA T4	PKAN T1	PKAN T2	PKAN T3
PWGM T1	SMBU T1	SONG T1	SONG T2
TJBU T1	TJBU T2	TKLG T1	TKLG T2
TMID T1	TMID T2	TMIP T1	TMIP T2

S.P MELAKA

AHTM A1	AKRH T1	AKRH T2	BTBM ET1
BTBM ET2	BTBM ET3	BTBM ET4	BTBM T1
BTBM T2	BTBM T3	BTBM T4	BVTA T1
BVTA T2	CAAH T1	CAAH T2	CHNG ET1
CHNG ET2	CHNG T1	CHNG T2	GMAS ET1
GMAS ET2	GMAS T1	GMAS T2	HLNM T1
HLNM T2	JSIN ET1	JSIN ET2	KGDK T1
KGDK T2	KLAT T2	KLMK T1	KLMK T2
MCCA ET1	MCCA SGT1	MCCA SGT2	MCCA T1
MCCA T2	MHKA T1	MHKA T2	MJYA T1
MJYA T2	MKTM T1	MLJY T1	MLMU T1
MMAU T1	MMAU T2	MMKA ET1	MMKA ET2
MMKA T1	MMKA T2	MPSS ET1	MPSS ET2
MPSS T1	MPSS T2	MTNH ET1	MTNH ET2
MTNH T1	MTNH T2	MUAR T1	MUAR T2
PBSR ET1	PBSR ET2	PBSR T1	PBSR T2
PGOH T1	PGOH T2	SABG ET1	SABG ET2
SABG T1	SABG T2	SGBG T1	SGBG T2
SGMT T1	SGMT T2	SGMT T3	SGMT66 T1
SGMT66 T2	SGMT66 T3	SMBK T1A	SMBK T2A
SMTI T1	SMTI T2	TG BATU T1	TGBU ET1
TGBU ET2	TGBU T1	TGBU T2	TGLN T1
TKAK T1	TKAK T2	TLBH T1	

S.P PETALLING JAYA

BAHA T1	BAHA T2	BKPY T1	BKPY T2
BRNG T1	BRNG T2	CJYA T1	CMBG T1
CMBG T2	CYJA T2	GMS2 T1	GMS2 T2
HLON T1	HLON T2	KAWA T3	KJNG ET3
KJNG T1	KJNG T3	KJNG T4	KKLW T1
KKLW T2	KLAT T1	KLPP T1	KPLH LMT1
KPLH T1	KPLH T2	LKUT T1	LKUT T2
MTIM T1	MTIM T2	MWTA T1	NLAI T1
NLAI T2	NUNI T1	NUNI T2	NUNI T3
NUNI T4	PDPD GT1	PDPS GT2	PDPS GT3
PDPS GT4	PDPS SGT1	PDRTM T1	PDSN T1
RASA T1	RASA T2	RTAU T1	RTAU T2
SBAN IT2	SBAN ITI	SBAN T1	SBAN T2
SLT1 SGT2	SLTI T1	SLTI T2	SMRK T1
SMRK T2	SMSG T1	SMSG T2	SMYH T1
SMYH T2	SNWG T1	SNWG T2	SNWG T3
SNWG T4	SPTG IT1	SPTG IT2	SPTG T1
SPTG T2	SRDG AT2	SRDG AT3	SRDG GT1

SRDG GT2	SRDG GT3	SRDG GT4	SRDG GT5
SRDG SGT1	SRDG T1	SRDG T2	SSUN T1
SSWW T1	SSWW T2	STRA T1	STRA T2
TJIP T1	TJIP T2	TJPS AUTX	TJPS AUX1
TJPS AUX2	TJPS G3	TJPS G4	TJPS G5
TJPS G6	TJPS G7	TJPS G8	TJPS GT1
TJPS GT2	TJPS SGT1	TJPS SGT2	TJPS T1
TJPS T2	TKMG T1	TKMG T2	TTJF T1
TTJF T2			

S.P TANAH MERAH

APMR T1	CHRG T1	CHRG T2	GMSG T1
KBRG T1	KBRG T2	KBRU T1	KBRU T2
KKRI T1	KKRI T2	KNYR SGT1	KNYR SGT2
KNYR T1	KNYR T2	KNYR T3	KNYR T4
LMAL T1	LMAL T2	PGAU T1	PGAU T2
PPTH T1	PPTH T2	SJTH T1	SJTH T2
TMRH GT1	TMRH GT2	TMRH SGT1	TMRH SGT2
TMRH T1			

APPENDIX B

EXAMPLE OF HYUNDAI TRANSFORMER MAINTENANCE GUIDE

Daily Inspection and Maintenance

No	Item	Content and Notes
1	Transformer temperature	1) Check and record the oil and winding temperature indicator. 2) Record ambient temperature, load and voltage. Explanatory Notes: 1) The transformer temperature directly affects the life of the insulating material. 2) The maximum temperature rise limits are specified for both oil and winding temperature. During the daily inspection, check not only that temperatures are within the maximum limit, but also that these temperatures lie within a satisfactory range by comparing their values with the test results in the test report, load conditions and ambient temperature.
2	Oil Level	1) Check and record the level of oil shown by the oil level indicator. 2) Check that the glass of oil level indicator is not dirty.
3	Noise	1) Check for any abnormal sound and vibration etc. Explanatory Notes: Learn by hearing an average, regular sound; If an irregular

		noise is heard, the problem should remember the normal sound made by transformer and further investigation should be done immediately.
4	Oil Leakage	1) Check for oil leaks at any connections such as valves, meters and particularly welding points.
5	Breather	1) Pay attention to the discoloration of the silica gel. 2) Check the level of the sealing oil in oil cup.
6	Pressure relief	1) Check for cracks, damages and traces of oil spouting in the pressure relief device, if plate is provided.
7	Cooling equipment	1) Check for oil leaks. 2) As regards forced oil cooled or fan cooled type: - Check for abnormal rotating sounds and vibrations. - Check for dust on radiator surface.
8	On load tap changer	1) Check for operating sounds. 2) Check whether the tap position is correct or not. 3) Record the number of tap changing operations. 4) Check the oil level gauge of OLTC conservator.
9	Off-circuit tap changer	1) Check whether the tap position is correct or not. * Note : Do not change the tapping when the transformer is on load.
10	Bushing	1) If the bushing is provided with oil level gauge, check oil level and oil leaks. 2) Visual check the extent of any contamination on the bushing. 3) Check the over heat of terminals.
11	Buchholz relay	1) Check whether it is filled up with gas.
12	Loose connections and valve	1) Check for any loose connections such as found in main circuits, grounding circuits, auxiliary circuits, foundation bolts and the like. 2) Valves are vulnerable to vibration. These should be

		checked particularly carefully.
13	Gas leakage	1) In the case of N2 gas sealed transformer, measure the nitrogen gas pressure and check for gas leaks.
14	Instrument	1) Check indicators and relays.
15	The others	1) Abnormal exciting noise and vibration.

Periodical Inspection

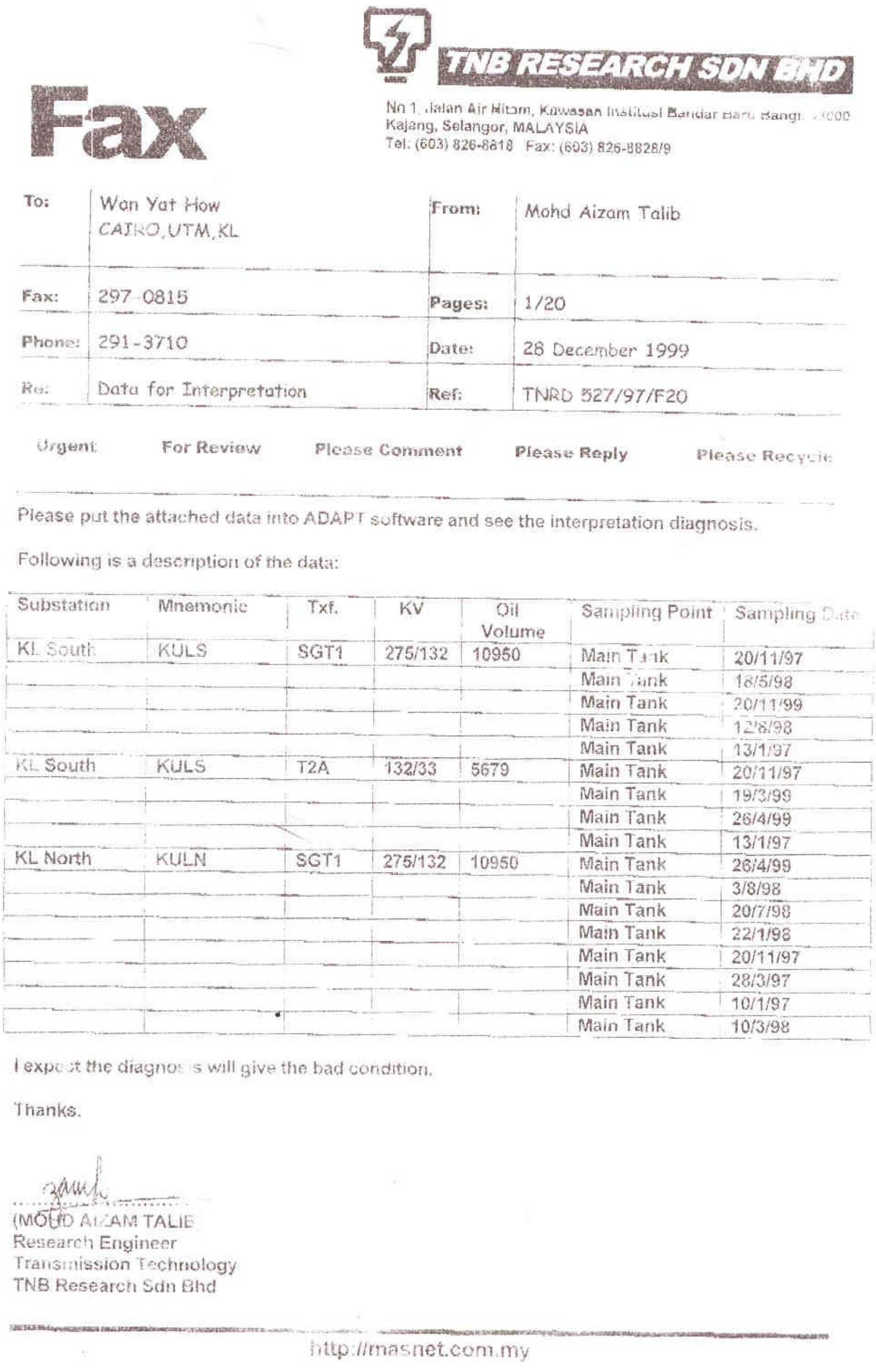
No	Inspection Items		Period	Criteria
1	Insulation oil	1) Measurement of dielectric strength.	Annually	More than 40KV/ 2.5 mm gap
		2) Measurement of acid value	Annually	Less than 0.2
		3) Tests specified in IEC-296.	-	To be carried out only when the dielectric strength and acid value are below standard.
2	Insulating of winding	1) Measurement of the insulation resistance between windings, and between winding and ground with a 2000 V megger.	2 or 3 years	
3	Fan motor / oil pump motor	1) Insulation resistance 2) Abnormal sound and vibration.	6 months	More than 2 M Ω
4	Off-circuit tap changer	1) Check for operation 2) Check for any oil leaks	annually	
5	On-load tap changer	Refer to separate instruction		
6	Bushing	1) Inspection of local heating	2 or 3 years	1) When contaminatio

		2) Check for any oil leaks 3) Check for oil level if provided 4) Check for any pollution or danger to the bushing		ns are excessive, clean up them.
7	Protective relays	1) Check for external construction, 2) Check for operating and insulation resistance. For thermometer, level gauge, flow indicator, gas detector, pressure relay, vacuum gauge etc.	2 or 3 years	More than 2 MΩ
8	Control panel and terminal box	1) Check the water-tightness	2 or 3 years	1) Exchange the gasket with a new one.
		2) Check the tightness of all connections.		1) Tighten the loose bolts
		3) Operation of all switches, annunciators and lamps to observe proper functions according to schematic diagrams.	Annually	1) If any part mal-operates, adjust or exchange them with new one.
		4) Insulating resistance	2 or 3 years	More than 2 MΩ
9	Breather	1) Check the discoloration of silica gel in breather due to moisture in breathed air.	6 months	Refer to separate instruction manual.

10	External of transformer	1) Check transformer tank and its accessories for any oil leak, rust, coating damage.	Annually	Repair and recoating of surface.
		1) Check to see whether all connections are in good conditions or not.		Tighten the loose all connection.

APPENDIX C

CASE STUDY 1



Fax

TNB RESEARCH SDN BHD

No 1, Jalan Air Hitam, Kawasan Institusi Bandar Baru Bangi, 43000
Kajang, Selangor, MALAYSIA
Tel: (603) 826-8818 Fax: (603) 826-8828/9

To:	Wan Yat How CAIRO, UTM, KL	**From:**	Mohd Aizam Talib
Fax:	297-0815	**Pages:**	1/20
Phone:	291-3710	**Date:**	28 December 1999
Re:	Data for Interpretation	**Ref:**	TNRD 527/97/F20

Urgent **For Review** **Please Comment** **Please Reply** **Please Recycle**

Please put the attached data into ADAPT software and see the interpretation diagnosis.

Following is a description of the data:

Substation	Mnemonic	Txf.	KV	Oil Volume	Sampling Point	Sampling Date
KL South	KULS	SGT1	275/132	10950	Main Tank	20/11/97
					Main Tank	18/5/98
					Main Tank	20/11/99
					Main Tank	12/8/98
					Main Tank	13/1/97
KL South	KULS	T2A	132/33	5679	Main Tank	20/11/97
					Main Tank	19/3/99
					Main Tank	26/4/99
					Main Tank	13/1/97
KL North	KULN	SGT1	275/132	10950	Main Tank	26/4/99
					Main Tank	3/8/98
					Main Tank	20/7/98
					Main Tank	22/1/98
					Main Tank	20/11/97
					Main Tank	28/3/97
					Main Tank	10/1/97
					Main Tank	10/3/98

I expect the diagnosis will give the bad condition.

Thanks.

(MOHD AIZAM TALIB
Research Engineer
Transmission Technology
TNB Research Sdn Bhd

http://masnet.com.my

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY :	TNB		
DIVISION :	S.P. Kuala Lumpur	**SITE:**	K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	13/01/97
Oil Temperature	
Receipt Date	30/01/97
Test Date	12/03/97
Colour	Brown
Analyst	NA

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	**Concentration / ppm**
Hydrogen	25
Oxygen	199
Nitrogen	165
Methane	73
Carbon Monoxide	212
Carbon Dioxide	1783
Ethylene	134
Ethane	17
Acetylene	Nil
n-Propane	74

2. MOISTURE CONTENT

Moisture Content / ppm	Nil

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	Nil

[B] CONDITION ASSESSMENT

DGA:	Ethylene gas level is slightly high. Recommend resample of oil in 2 months for retest.
Moisture:	Nil
Acidity:	Nil

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 461 ppm
Previous TDCG = 0 ppm
Sampling Duration = 0 days
TDCG Rate = 0 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 0 ppm

Gases Over Limit Value:
Current C2H4 = 134 ppm
Previous C2H4 = 0 ppm

Fluid Quality:
None

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%

Note:
None

Advices :
- This is the first test record. Recommend oil resampling interval= 6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is most probably in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 76.67%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Heating

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	20/11/97
Oil Temperature	
Receipt Date	21/11/97
Test Date	26/11/97
Colour	Brown
Analyst	Mas

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	60
Oxygen	515
Nitrogen	898
Methane	119
Carbon Monoxide	122
Carbon Dioxide	1006
Ethylene	206
Ethane	18
Acetylene	3
n-Propane	89

2. MOISTURE CONTENT

Moisture Content / ppm	49

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.17

[B] CONDITION ASSESSMENT

DGA:	Hydrogen, Methane and Ethylene gas values are high, possibly due to overheating. Recommend investigating and resample for retest.
Moisture:	Above normal value of 30 ppm
Acidity:	Normal

ADAPT INTERPRETATION

<< *MAIN INTERPRETATION* >>

TDCG Level Summary:
Current TDCG = 528 ppm
Previous TDCG = 461 ppm
Sampling Duration = 311 days
TDCG Rate = 0.22 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 5.78 ppm

Gases Over Limit Value:
Current C2H4 = 206 ppm
Previous C2H4 = 134 ppm

Fluid Quality:
Current Moisture = 49 ppm
Previous Moisture = 0 ppm

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%
Oil Oxidation - 100%

Note:
- The Moisture/Acidity content is higher than the normal condition.
- The oil may need reclamation for further service.
- Oil seems to be oxidized and may be forming sludge which can deteriorate the heat transfer of oil and causing the transformer to operate at a high temperature.
- Check the power factor and dielectric strength of the oil.

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< *SUPPORTIVE INTERPRETATION* >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Oil Oxidation - 100%

Logarithmic Nomograph Method:
Heating

Contradict Case 1

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	18/05/98
Oil Temperature	
Receipt Date	25/05/98
Test Date	25/05/98
Colour	Brown
Analyst	Mas & Zamran

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	17
Oxygen	210
Nitrogen	544
Methane	36
Carbon Monoxide	28
Carbon Dioxide	20
Ethylene	53
Ethane	12
Acetylene	7
n-Propane	17

2. MOISTURE CONTENT

Moisture Content / ppm	45

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.13

[B] CONDITION ASSESSMENT

DGA: Ethylene gas value is high, possibly due to arcing. Recommend investigation and resample for retest. (INITIAL INTERPRETATION)

Thermal heating / Overheating (VERIFIED INTERPRETATION)

Moisture: Above normal value of 30 ppm

Acidity: Normal

ADAPT INTERPRETATION

<< *MAIN INTERPRETATION* >>

TDCG Level Summary:
Current TDCG = 153 ppm
Previous TDCG = 528 ppm
Sampling Duration = 179 days
TDCG Rate = -2.09 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 1.68 ppm

Gases Over Limit Value:
Current C2H4 = 53 ppm
Previous C2H4 = 206 ppm

Fluid Quality:
Current Moisture = 45 ppm
Previous Moisture = 49 ppm

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%
Oil Oxidation - 100%

Note:
- The Moisture/Acidity content is higher than the normal condition.
- The oil may need reclamation for further service.
- Oil seems to be oxidized and may be forming sludge which can deteriorate the heat transfer of oil and causing the transformer to operate at a high temperature.
- Check the power factor and dielectric strength of the oil.

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< *SUPPORTIVE INTERPRETATION* >>

Fuzzy Rogers Ratio Method:
No Matched Interpretation

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Oil Oxidation - 100%

Logarithmic Nomograph Method:
Heating

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	12/08/98
Oil Temperature	
Receipt Date	14/08/98
Test Date	05/09/98
Colour	Brown
Analyst	Mas, Zamran, Ayu

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	Nil
Oxygen	30758
Nitrogen	100444
Methane	196
Carbon Monoxide	157
Carbon Dioxide	933
Ethylene	303
Ethane	41
Acetylene	6
n-Propane	68

2. MOISTURE CONTENT

Moisture Content / ppm	48

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.13

[B] CONDITION ASSESSMENT

DGA:	Methane, Ethane and Ethylene gas values are high possibly due to some overheating. Advise investigation and resample for retest
Moisture:	Above normal value of 30 ppm
Acidity:	Normal

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 703 ppm
Previous TDCG = 153 ppm
Sampling Duration = 86 days
TDCG Rate = 6.4 ppm/day
Gas In Ft3 = 0.01 ft3/day
TCGv = 7.7 ppm

Gases Over Limit Value:
Current C2H4 = 303 ppm
Previous C2H4 = 53 ppm

Current CH4 = 196 ppm
Previous CH4 = 36 ppm

Fluid Quality:
Current Moisture = 48 ppm
Previous Moisture = 45 ppm

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%
Low Temperature Oil Breakdown - 100%
Oil Oxidation - 100%

Note:
- The Moisture/Acidity content is higher than the normal condition.
- The oil may need reclamation for further service.
- Oil seems to be oxidized and may be forming sludge which can deteriorate the heat transfer of oil and causing the transformer to operate at a high temperature.
- Check the power factor and dielectric strength of the oil.

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio
Gas Hydrogen is NIL !
Not enough information for Rogers ratio Interpretation!

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Low Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Oil Oxidation - 100%

Logarithmic Nomograph Method:
Heating
Discharge & Heating

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY :	TNB		
DIVISION :	S.P. Kuala Lumpur	**SITE:**	K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	20/11/99
Oil Temperature	
Receipt Date	21/11/99
Test Date	24/11/99
Colour	Brown
Analyst	

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	2363
Oxygen	10461
Nitrogen	23700
Methane	213
Carbon Monoxide	3
Carbon Dioxide	322
Ethylene	1129
Ethane	83
Acetylene	1537
n-Propane	NIL

2. MOISTURE CONTENT

Moisture Content / ppm	59

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.15

[B] CONDITION ASSESSMENT

DGA:	The values of fault gases are very high, possibly due to high energy arcing. Advise investigation and retest.
Moisture:	Above normal value of 30 ppm
Acidity:	Normal

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 5328 ppm
Previous TDCG = 703 ppm
Sampling Duration = 465 days
TDCG Rate = 9.95 ppm/day
Gas In Ft3 = 0.01 ft3/day
TCGv = 58.34 ppm

Gases Over Limit Value:
Current H_2 = 2363 ppm
Previous H_2 = 0 ppm

Current C_2H_2 = 1537 ppm
Previous C_2H_2 = 6 ppm

Current C_2H_4 = 1129 ppm
Previous C_2H_4 = 303 ppm

Current C_2H_6 = 83 ppm
Previous C_2H_6 = 41 ppm

Current CH_4 = 213 ppm
Previous CH_4 = 196 ppm

Fluid Quality:
Current CO_2/CO = 107.333333333333
Previous CO_2/CO = 5.94267515923567

Current Moisture = 59 ppm
Previous Moisture = 48 ppm

Summary of Diagnosis:
Arcing - 100%
Corona/Partial Discharge - 100%
High Temperature Oil Breakdown - 100%
Low Temperature Oil Breakdown - 100%
Oil Oxidation - 100%

Note:
- The Moisture/Acidity content is higher than the normal condition.
- The oil may need reclamation for further service.
- Oil seems to be oxidized and may be forming sludge which can deteriorate the heat transfer of oil and causing the transformer to operate at a high temperature.
- Check the power factor and dielectric strength of the oil.

Advices :
- Recommended operating procedure:-
  Exercise caution.
  Analyse for individual gases.
  Plan outage

- Preferable oil resampling interval:-
  Weekly

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
No Matched Interpretation

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : Arcing - 100%
The transformer is in critical condition of fault : Corona/Partial Discharge - 100%
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Low Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Oil Oxidation - 100%

Logarithmic Nomograph Method:
Arcing
Heating

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	10/01/97
Oil Temperature	
Receipt Date	30/01/97
Test Date	11/03/97
Colour	Brown
Analyst	NA

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	**Concentration / ppm**
Hydrogen	69
Oxygen	165
Nitrogen	141
Methane	146
Carbon Monoxide	405
Carbon Dioxide	1773
Ethylene	257
Ethane	34
Acetylene	3
n-Propane	115

2. MOISTURE CONTENT

Moisture Content / ppm	NIL

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	NIL

[B] CONDITION ASSESSMENT

DGA: Fault gas levels are high, possibly due to overheating. Recommend resample within 1 month for retest.

Moisture: NIL

Acidity: NIL

ADAPT INTERPRETATION

<< *MAIN INTERPRETATION* >>

TDCG Level Summary:
Current TDCG = 914 ppm
Previous TDCG = 0 ppm
Sampling Duration = 0 days
TDCG Rate = 0 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 0 ppm

Gases Over Limit Value:
Current C2H4 = 257 ppm
Previous C2H4 = 0 ppm

Current CH4 = 146 ppm
Previous CH4 = 0 ppm

Fluid Quality:
None

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%
Low Temperature Oil Breakdown - 100%

Note:
None

Advices :
- This is the first test record. Recommend oil resampling interval= 6 months

<< *SUPPORTIVE INTERPRETATION* >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Low Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Heating
Discharge & Heating

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	28/03/97
Oil Temperature	
Receipt Date	29/04/97
Test Date	30/04/97
Colour	Brown
Analyst	NA

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	53
Oxygen	152
Nitrogen	140
Methane	129
Carbon Monoxide	284
Carbon Dioxide	2172
Ethylene	255
Ethane	38
Acetylene	3
n-Propane	139

2. MOISTURE CONTENT

Moisture Content / ppm	18

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.2

[B] CONDITION ASSESSMENT

DGA: No further increase of fault gases. However, we recommend resample of oil in 3 months for retest.

Moisture: NIL

Acidity: NIL

ADAPT INTERPRETATION

<< *MAIN INTERPRETATION* >>

TDCG Level Summary:
Current TDCG = 762 ppm
Previous TDCG = 914 ppm
Sampling Duration = 77 days
TDCG Rate = -1.97 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 8.34 ppm

Gases Over Limit Value:
Current C2H4 = 255 ppm
Previous C2H4 = 257 ppm

Current CH4= 129 ppm
Previous CH4 = 146 ppm

Fluid Quality:
None

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%
Low Temperature Oil Breakdown - 100%

Note:
None

Advices :
- Most encouragable operating procedure:-
  Exercise caution.
  Analyse for individual gases.
  Determine load dependence.
- Most encouragable oil resampling interval:-
  Quartely

<< *SUPPORTIVE INTERPRETATION* >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Low Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Heating
Discharge & Heating

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	20/11/97
Oil Temperature	
Receipt Date	21/11/97
Test Date	21/11/97
Colour	Brown
Analyst	NA

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	249
Oxygen	344
Nitrogen	501
Methane	323
Carbon Monoxide	172
Carbon Dioxide	933
Ethylene	556
Ethane	29
Acetylene	9
n-Propane	199

2. MOISTURE CONTENT

Moisture Content / ppm	9

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	NIL

[B] CONDITION ASSESSMENT

DGA:	The values of fault gases are very high, possibly due to much overheating. Advise investigation and retest.
Moisture:	Normal
Acidity:	NIL

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 1338 ppm
Previous TDCG = 762 ppm
Sampling Duration = 237 days
TDCG Rate = 2.43 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 14.65 ppm

Gases Over Limit Value:
Current H2 = 249 ppm
Previous H2 = 53 ppm

Current C2H4 = 556 ppm
Previous C2H4 = 255 ppm

Current CH4 = 323 ppm
Previous CH4 = 129 ppm

Fluid Quality:
None

Summary of Diagnosis:
Corona/Partial Discharge - 100%
High Temperature Oil Breakdown - 100%
Low Temperature Oil Breakdown - 100%

Note:
None

Advices :
- Most encouragable operating procedure:-
  Exercise caution.
  Analyse for individual gases.
  Determine load dependence.
- Most encouragable oil resampling interval:-
  Quartely

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : Corona/Partial Discharge - 100%
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Low Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Heating
Discharge & Heating

Contradict Case 2

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY :	TNB		
DIVISION :	S.P. Kuala Lumpur	**SITE:**	K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	22/01/98
Oil Temperature	
Receipt Date	23/01/98
Test Date	19/02/98
Colour	Brown
Analyst	NA

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	87
Oxygen	8548
Nitrogen	766
Methane	110
Carbon Monoxide	113
Carbon Dioxide	671
Ethylene	314
Ethane	44
Acetylene	5
n-Propane	75

2. MOISTURE CONTENT

Moisture Content / ppm	11

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.09

[B] CONDITION ASSESSMENT

DGA: The values of fault gases are very high, possibly due to high energy arcing. Advice investigation and retest. (INITIAL INTERPRETATION)

Thermal heating of oil at high temperature (VERIFIED INTERPRETATION)

Moisture: Normal

Acidity: Normal

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 675 ppm
Previous TDCG = 1338 ppm
Sampling Duration = 63 days
TDCG Rate = -10.52 ppm/day
Gas In Ft3 = -0.02 ft3/day
TCGv = 7.39 ppm

Gases Over Limit Value:
Current C2H4 = 314 ppm
Previous C2H4 = 556 ppm

Fluid Quality:
None

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%

Note:
None

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Heating

Contradict Case 3

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	10/03/98
Oil Temperature	
Receipt Date	13/03/98
Test Date	19/03/98
Colour	Brown
Analyst	Mas & Zamran

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	26
Oxygen	1019
Nitrogen	807
Methane	54
Carbon Monoxide	31
Carbon Dioxide	257
Ethylene	93
Ethane	13
Acetylene	1
n-Propane	30

2. MOISTURE CONTENT

Moisture Content / ppm	14

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.06

[B] CONDITION ASSESSMENT

DGA: The values of fault gases are high, possibly due to high energy arcing. Advice investigation and retest. (INITIAL INTERPRETATION)

Thermal heating of oil at high temperature. (VERIFIED INTERPRETATION)

Moisture: Normal

Acidity: Normal

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 218 ppm
Previous TDCG = 675 ppm
Sampling Duration = 47 days
TDCG Rate = -9.72 ppm/day
Gas In Ft3 = -0.01 ft3/day
TCGv = 2.39 ppm

Gases Over Limit Value:
Current C2H4 = 93 ppm
Previous C2H4 = 314 ppm

Fluid Quality:
None

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%

Note:
None

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Heating

Contradict Case 4

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	20/07/98
Oil Temperature	
Receipt Date	25/07/98
Test Date	20/08/98
Colour	Brown
Analyst	Mas

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	Nil
Oxygen	39120
Nitrogen	100880
Methane	13
Carbon Monoxide	10
Carbon Dioxide	151
Ethylene	24
Ethane	4
Acetylene	Nil
n-Propane	17

2. MOISTURE CONTENT

Moisture Content / ppm	5

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.05

[B] CONDITION ASSESSMENT

DGA: Ethylene gas value is slightly high probably due to overheating. (INITIAL INTERPRETATIO)

Normal (VERIFIED INTERPRETATION)

Moisture: Normal

Acidity: Normal

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 51 ppm
Previous TDCG = 218 ppm
Sampling Duration = 132 days
TDCG Rate = -1.27 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 0.56 ppm

Gases Over Limit Value:
None

Fluid Quality:
Current CO2/CO = 15.1
Previous CO2/CO = 8.29032258064516

Summary of Diagnosis:
Normal Condition

Note:
None

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio
Gas Hydrogen is NIL !
Not enough information for Rogers ratio Interpretation!

Fuzzy Key Gases Method:
The transformer is in normal condition

Logarithmic Nomograph Method:
No Fault Detected!

Contradict Case 5

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	03/08/98
Oil Temperature	
Receipt Date	07/08/98
Test Date	17/08/98
Colour	Brown
Analyst	Mas, Zamran, Ayu

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	Nil
Oxygen	37051
Nitrogen	97873
Methane	24
Carbon Monoxide	17
Carbon Dioxide	171
Ethylene	39
Ethane	6
Acetylene	Nil
n-Propane	19

2. MOISTURE CONTENT

Moisture Content / ppm	15

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.05

[B] CONDITION ASSESSMENT

DGA: Ethylene gas value is high, probably due to overheating, recommend to resample and retest. (INITIAL INTERPRETATION)

Normal. (VERIFIED INTERPRETATION)

Moisture: Normal.

Acidity: Normal.

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 86 ppm
Previous TDCG = 51 ppm
Sampling Duration = 14 days
TDCG Rate = 2.5 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 0.94 ppm

Gases Over Limit Value:
None

Fluid Quality:
Current CO2/CO = 10.0588235294118
Previous CO2/CO = 15.1

Summary of Diagnosis:
Normal Condition

Note:
None

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio
Gas Hydrogen is NIL !
Not enough information for Rogers ratio Interpretation!

Fuzzy Key Gases Method:
The transformer is in normal condition

Logarithmic Nomograph Method:
No Fault Detected!

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. North

TRANSFORMER IDENTIFICATION	
TX No.	SGT1
Serial No.	
Load MVA	180
Voltages/ kV	275 / 132
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	26/04/99
Oil Temperature	
Receipt Date	26/04/99
Test Date	26/04/99
Colour	Brown
Analyst	Zamran, Ayu

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	154
Oxygen	20322
Nitrogen	48961
Methane	93
Carbon Monoxide	236
Carbon Dioxide	533
Ethylene	184
Ethane	21
Acetylene	189
n-Propane	NIL

2. MOISTURE CONTENT

Moisture Content / ppm	18

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.04

[B] CONDITION ASSESSMENT

DGA: The values of fault gases are very high, possibly due to high energy arcing. Advise investigation and retest.

Moisture: Normal.

Acidity: Normal.

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 877 ppm
Previous TDCG = 86 ppm
Sampling Duration = 266 days
TDCG Rate = 2.97 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 9.6 ppm

Gases Over Limit Value:
Current H2 = 154 ppm
Previous H2 = 0 ppm

Current C2H2 = 189 ppm
Previous C2H2 = 0 ppm

Current C2H4 = 184 ppm
Previous C2H4 = 39 ppm

Fluid Quality:
None

Summary of Diagnosis:
Arcing - 100%
Corona/Partial Discharge - 100%
High Temperature Oil Breakdown - 100%

Note:
None

Advices :
- Most encouragable operating procedure:-
  Exercise caution.
  Analyse for individual gases.
  Determine load dependence.
- Most encouragable oil resampling interval:-
  Quartely

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in High Energy Discharge: Arc with Power Follow Through - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : Arcing - 100%
The transformer is in critical condition of fault : Corona/Partial Discharge - 100%
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Arcing
Heating

Contradict Case 6

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	T2A
Serial No.	
Load MVA	30
Voltages/ kV	132 / 33
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	13/01/97
Oil Temperature	
Receipt Date	30/01/97
Test Date	12/03/97
Colour	Brown
Analyst	NA

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	30
Oxygen	84
Nitrogen	122
Methane	30
Carbon Monoxide	333
Carbon Dioxide	2755
Ethylene	58
Ethane	9
Acetylene	NIL
n-Propane	43

2. MOISTURE CONTENT

Moisture Content / ppm NIL

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample) NIL

[B] CONDITION ASSESSMENT

DGA: Oil is normal. (INITIAL INTERPRETATION)

Thermal heating involved oil and cellulose. (VERIFIED INTERPRETATION)

Moisture: NIL

Acidity: NIL

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 460 ppm
Previous TDCG = 0 ppm
Sampling Duration = 0 days
TDCG Rate = 0 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 0 ppm

Gases Over Limit Value:
Current C2H4 = 58 ppm
Previous C2H4 = 0 ppm

Fluid Quality:
None

Summary of Diagnosis:
High Temperature Oil Breakdown - 100%
Cellulose Insulation Breakdown - 97.14%

Note:
None

Advices :
- This is the first test record. Recommend oil resampling interval= 6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is probably in Thermal Fault of High Temp.Range 300-700 Degree Celsius:Bad Contacts/Joints(pyrolytic carbon formation) - 50%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%
The transformer is in critical condition of fault : Cellulose Insulation Breakdown - 97.14%

Logarithmic Nomograph Method:
Heating

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	T2A
Serial No.	
Load MVA	30
Voltages/ kV	132 / 33
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	20/11/97
Oil Temperature	
Receipt Date	21/11/97
Test Date	24/11/97
Colour	Brown
Analyst	NA

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	**Concentration / ppm**
Hydrogen	11
Oxygen	344
Nitrogen	664
Methane	7
Carbon Monoxide	112
Carbon Dioxide	1335
Ethylene	11
Ethane	2
Acetylene	NIL
n-Propane	9

2. MOISTURE CONTENT

Moisture Content / ppm	40

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.11

[B] CONDITION ASSESSMENT

DGA:	Normal
Moisture:	Above normal value of 30 ppm.
Acidity:	Normal.

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 143 ppm
Previous TDCG = 460 ppm
Sampling Duration = 311 days
TDCG Rate = -1.02 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 0.81 ppm

Gases Over Limit Value:
None

Fluid Quality:
Current CO2/CO = 11.9196428571429
Previous CO2/CO = 8.27327327327327

Current Moisture = 40 ppm
Previous Moisture = 0 ppm

Summary of Diagnosis:
Oil Oxidation - 100%

Note:
- The Moisture/Acidity content is higher than the normal condition.
- The oil may need reclamation for further service.
- Oil seems to be oxidized and may be forming sludge which can deteriorate the heat transfer of oil and causing the transformer to operate at a high temperature.
- Check the power factor and dielectric strength of the oil.

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
No Matched Interpretation

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : Oil Oxidation - 100%

Logarithmic Nomograph Method:
No Fault Detected!

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	T2A
Serial No.	
Load MVA	30
Voltages/ kV	132 / 33
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	MAIN TANK
Sampling Date	19/03/99
Oil Temperature	
Receipt Date	19/03/99
Test Date	19/03/99
Colour	Dark Brown
Analyst	Zamran & Ayu

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	Concentration / ppm
Hydrogen	153
Oxygen	996
Nitrogen	1714
Methane	23
Carbon Monoxide	23
Carbon Dioxide	90
Ethylene	36
Ethane	3
Acetylene	117
n-Propane	3

2. MOISTURE CONTENT

Moisture Content / ppm	25

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.07

[B] CONDITION ASSESSMENT

DGA: The values of fault gases are very high, possibly due to high energy arcing. Advise investigation and retest.

Moisture: Normal.

Acidity: Normal.

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 355 ppm
Previous TDCG = 143 ppm
Sampling Duration = 484 days
TDCG Rate = 0.44 ppm/day
Gas In Ft3 = 0 ft3/day
TCGv = 2.02 ppm

Gases Over Limit Value:
Current H2 = 153 ppm
Previous H2 = 11 ppm

Current C2H2 = 117 ppm
Previous C2H2 = 0 ppm

Fluid Quality:
None

Summary of Diagnosis:
Arcing - 100%
Corona/Partial Discharge - 100%

Note:
None

Advices :
- Most encouragable operating procedure:-
  Continue normal operation
- Most encouragable oil resampling interval:-
  6 months

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is absolutely in High Energy Discharge: Arc with Power Follow Through - 100%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : Arcing - 100%
The transformer is in critical condition of fault : Corona/Partial Discharge - 100%

Logarithmic Nomograph Method:
Arcing

TNRD OIL & INSULATION LABORATORY
INSULATING OIL TEST REPORT

COMPANY : TNB
DIVISION : S.P. Kuala Lumpur **SITE:** K.L. South

TRANSFORMER IDENTIFICATION	
TX No.	T2A
Serial No.	
Load MVA	30
Voltages/ kV	132 / 33
Make	
Year Built	

OIL SAMPLE IDENTIFICATION	
Sampling Point	
Sampling Date	26/04/99
Oil Temperature	
Receipt Date	26/04/99
Test Date	26/04/99
Colour	Brown
Analyst	Mas

[A] RESULT

1. DISSOLVED GAS ANALYSIS

Gas Type	**Concentration / ppm**
Hydrogen	324
Oxygen	13960
Nitrogen	35428
Methane	98
Carbon Monoxide	110
Carbon Dioxide	1086
Ethylene	185
Ethane	15
Acetylene	575
n-Propane	NIL

2. MOISTURE CONTENT

Moisture Content / ppm	30

3. TOTAL ACIDITY

Total Acidity / (mg KOH/g sample)	0.02

[B] CONDITION ASSESSMENT

DGA: The values of fault gases are very high, possibly due to high energy arcing. Advise investigation and retest.

Moisture: Normal.

Acidity: Normal.

ADAPT INTERPRETATION

<< MAIN INTERPRETATION >>

TDCG Level Summary:
Current TDCG = 1307 ppm
Previous TDCG = 355 ppm
Sampling Duration = 38 days
TDCG Rate = 25.05 ppm/day
Gas In Ft3 = 0.02 ft3/day
TCGv = 7.42 ppm

Gases Over Limit Value:
Current H2 = 324 ppm
Previous H2 = 153 ppm

Current C2H2 = 575 ppm
Previous C2H2 = 117 ppm

Current C2H4 = 185 ppm
Previous C2H4 = 36 ppm

Fluid Quality:
None

Summary of Diagnosis:
Arcing - 100%
Corona/Partial Discharge - 100%
High Temperature Oil Breakdown - 100%

Note:
None

Advices :
- Most encouragable operating procedure:-
  Exercise caution.
  Analyse for individual gases.
  Determine load dependence.
- Most encouragable oil resampling interval:-
  Monthly

<< SUPPORTIVE INTERPRETATION >>

Fuzzy Rogers Ratio Method:
The transformer is most probably in High Energy Discharge: Arc with Power Follow Through - 86.04%

Fuzzy Key Gases Method:
The transformer is in critical condition of fault : Arcing - 100%
The transformer is in critical condition of fault : Corona/Partial Discharge - 100%
The transformer is in critical condition of fault : High Temperature Oil Breakdown - 100%

Logarithmic Nomograph Method:
Arcing

	Human Expert Interpretation	C2H2	H2	C2H6	CH4	C2H4	CO	R1	R2	R3	R4	**Rogers Ratio**	**Compare**	**Fuzzy Rogers Ratio**	**Compare**
1	High energy arcing, overheating and thermal decomposition involve cellulose	2883	7	82	181	1147	60	1	2	2	0	∅		∅	
2	High energy arcing, overheating, corona and thermal decomposition involve cellulose	1075	1559	418	447	73	1999	2	0	0	0	**F**	✓	**F**	✓
3	High energy arcing, overheating, corona and thermal decomposition involve cellulose	1045	1793	417	472	71	2199	2	0	0	0	**F**	✓	**F**	✓
4	High energy arcing, thermal decomposition involve cellulose and low overheating and corona	384	111	9	47	101	623	2	0	2	0	**H**	✓	**H**	✓
5	High energy arcing, thermal decomposition involve cellulose and low overheating and corona	337	121	8	38	98	392	2	0	2	0	**H**	✓	**H**	✓
6	High energy arcing	317	25	3	11	45	95	2	0	2	0	**H**	✓	**H**	✓
7	High energy arcing and overheating	268	12	5	50	363	4	1	2	2	0	∅		∅	
8	High energy arcing, overheating and thermal decomposition involve cellulose	233	74	12	12	69	492	2	0	2	1	∅		**0.5 – H**	✓
9	High energy arcing	218	88	4	13	20	187	2	0	2	0	**H**	✓	**H**	✓
10	High energy arcing	218	88	4	13	20	187	2	0	2	0	**H**	✓	**H**	✓
11	High energy arcing, corona and thermal decomposition involve cellulose	188	1482	23	79	29	548	2	5	1	0	∅		∅	
12	High energy arcing, corona and thermal decomposition involve cellulose	161	906	31	79	26	545	2	5	0	0	∅		∅	
13	High energy arcing and less corona	160	104	2	11	22	311	2	0	2	0	**H**	✓	**H**	✓
14	High energy arcing, corona and thermal decomposition involve cellulose	147	894	22	75	22	561	2	5	1	0	∅		∅	
15	High energy arcing	146	26	1	6	19	39	2	0	2	0	**H**	✓	**H**	✓
16	High energy arcing and thermal decomposition involve cellulose	132	26	28	11	68	552	1	0	1	1	∅		∅	
17	High energy arcing and corona	117	153	3	23	36	23	2	0	2	0	**H**	✓	**H**	✓
18	Arcing, overheating and thermal decomposition involve cellulose	98	27	23	16	127	571	1	0	2	1	∅		∅	
19	Arcing and thermal decomposition involve cellulose	97	43	20	13	101	377	1	0	2	1	∅		∅	
20	Arcing, corona and thermal decomposition involve cellulose	96	418	21	56	14	363	2	0	0	0	**F**	✓	**F**	✓
21	Arcing	84	20	5	12	36	209	1	0	2	0	**H**	✓	**H**	✓
22	Arcing	78	16	9	7	23	321	2	0	1	1	∅		∅	
23	Arcing	75	29	2	7	10	272	2	0	2	0	**H**	✓	**H**	✓
24	Arcing	75	29	2	7	10	272	2	0	2	0	**H**	✓	**H**	✓

25	Arcing	71	17	2	6	10	206	2	0	2	0	**H**	✓	**H**	✓
26	Arcing, corona and thermal decomposition involve cellulose	66	274	34	23	36	398	1	5	1	1	∅		∅	
27	Low energy arcing	56	16	4	5	17	210	2	0	2	0	**H**	✓	**H**	✓
28	Low energy arcing	53	20	6	5	19	237	1	0	2	1	∅		∅	
29	Low energy arcing and thermal decomposition involve cellulose	53	10	5	7	5	467	2	0	1	0	**G**	✓	**0.5 – F** **0.5 – G**	✓
30	Low energy arcing	52	46	15	22	31	315	1	0	1	0	**G**	✓	**G**	✓
31	Low energy arcing and thermal decomposition involve cellulose	52	21	8	8	2	412	2	0	0	1	∅		**0.5 – F**	✓
32	Low energy arcing	52	13	3	4	2	284	2	0	0	0	**F**	✓	**F**	✓
33	Low energy arcing and thermal decomposition involve cellulose	51	12	5	6	16	376	2	0	2	0	**H**	✓	**H**	✓
34	Low energy arcing	51	10	7	10	29	39	1	1	2	0	∅		**0.5 – H**	✓
35	Low energy arcing and corona	48	188	9	30	13	30	2	0	1	0	**G**	✓	**G**	✓
36	Low energy arcing, corona and thermal decomposition involve cellulose	45	121	11	21	32	380	1	0	1	0	**G**	✓	**0.803 – G** **0.197 – F**	✓
37	Low energy arcing	45	12	5	6	5	303	2	0	1	0	**G**	✓	**G**	✓
38	Low energy arcing and high corona	44	6305	10	14	20	257	1	5	1	0	∅		∅	
39	Low energy arcing	44	20	4	1	11	213	2	5	1	1	∅		∅	
40	Low energy arcing	42	55	11	32	12	0	2	0	1	0	**G**	✓	**G**	✓
41	Low energy arcing	40	21	7	92	45	34	1	2	2	0	∅		∅	
42	Low energy arcing and corona	36	283	6	18	14	62	1	5	1	0	∅		∅	
43	Low energy arcing	36	18	3	5	10	226	2	0	2	0	**H**	✓	**H**	✓
44	Low energy arcing	36	10	2	4	9	158	2	0	2	0	**H**	✓	**H**	✓
45	Normal	35	55	7	11	16	231	1	0	1	0	**G**	×	**G**	×
46	Thermal decomposition involve cellulose	33	9	17	43	11	409	1	2	0	0	∅		∅	
47	Overheating and thermal decomposition involve cellulose	30	28	19	55	107	457	1	1	2	0	∅		∅	
48	Overheating	21	8	5	316	21	28	1	2	2	0	∅		∅	
49	Thermal decomposition involve cellulose	20	32	35	61	9	502	1	1	0	0	**K**	✓	**K**	✓
50	Normal	19	11	82	47	17	201	1	2	0	1	∅		∅	
51	Normal	17	77	7	11	12	188	1	0	1	0	**G**	×	**G**	×
52	Overheating and thermal decomposition involve cellulose	17	49	4161	9	7	376	1	0	0	1	**K**	✓	**K**	✓
53	Normal	17	24	4	8	8	329	1	0	1	0	**G**	×	**G**	×
54	Normal	17	14	1	2	2	17	2	0	1	0	**G**	×	**G**	×

55	Corona	15	259	2	2	2	62	2	5	1	1	∅		∅	
56	Low corona	15	110	2	5	3	26	2	5	1	0	∅		∅	
57	Thermal decomposition involve cellulose	15	57	13	29	14	551	1	0	1	0	**G**	✓	**G**	✓
58	Normal	15	9	4	8	7	264	1	0	1	0	**G**	✗	**G**	✗
59	Normal	14	28	10	20	10	0	1	0	1	0	**G**	✗	**0.5 – G** **0.5 – F**	✗
60	Overheating	14	7	144	32	5	284	1	2	0	1	∅		∅	
61	Normal	13	5	2	2	2	63	2	0	1	1	∅		**0.5 – F** **0.5 – G**	✗
62	Thermal decomposition involve cellulose	8	37	17	6	3	401	1	0	0	1	**K**	✓	**K**	✓
63	Normal	8	25	2	4	11	215	1	0	2	0	**H**	✓	**H**	✓
64	Normal	7	8	1	3	3	177	1	0	1	0	**G**	✗	**0.5 – G** **0.5 – H**	✗
65	Normal	6	40	20	19	18	328	1	0	0	1	**K**	✗	**K**	✗
66	High corona	5	2131	36	24	33	316	1	5	0	1	∅		∅	
67	Corona	5	797	4	5	6	185	1	5	1	0	∅		∅	
68	Overheating	5	38	1	276	1567	7	0	2	2	0	**P**	✓	**P**	✓
69	Normal	5	24	13	12	15	230	1	0	1	1	∅		∅	
70	Normal	5	11	7	5	3	112	1	0	0	1	**K**	✗	**K**	✗
71	Normal	5	5	1	3	31	283	1	0	2	0	**H**	✗	**H**	✗
72	Corona and thermal decomposition involve cellulose	4	626	54	46	31	376	1	5	0	1	∅		∅	
73	Thermal decomposition involve cellulose	4	17	6	7	7	359	1	0	1	0	**G**	✗	**G**	✗
74	Corona	3	524	33	17	22	199	1	5	0	1	∅		∅	
75	Normal	3	5	1	4	23	315	1	0	2	0	**H**	✗	**H**	✗
76	High corona	2	1587	57	38	20	305	1	5	0	1	∅		**0.5 – E**	✓
77	Corona and Overheating	2	111	28	159	364	110	0	1	2	0	**P**	✓	**P**	✓
78	Overheating	2	74	26	187	388	154	0	1	2	0	**P**	✓	**P**	✓
79	Overheating	2	55	18	102	246	121	0	1	2	0	**P**	✓	**P**	✓
80	Overheating	2	37	12	71	166	133	0	1	2	0	**P**	✓	**P**	✓
81	Normal	2	26	2	4	3	282	1	0	1	0	**G**	✗	**G**	✗
82	Overheating	2	15	458	87	33	286	0	2	0	1	**N**	✓	**N**	✓
83	Normal	2	15	3	4	17	258	1	0	2	0	**H**	✗	**H**	✗

84	Overheating	2	8	52	48	281	130	0	2	2	1	**∅**		**∅**	
85	Normal	2	8	1	4	3	332	1	0	1	0	**G**	×	**0.5 – G** **0.5 – H**	×
86	Normal	1	51	14	25	10	187	1	0	0	0	**F**	×	**0.5 – F** **0.5 – A**	×
87	Overheating	1	47	24	137	324	148	0	1	2	0	**P**	✓	**0.7837 -P**	✓
88	Normal	1	26	2	4	3	303	1	0	1	0	**G**	×	**G**	×
89	Normal	1	21	6	6	4	254	1	0	0	1	**K**	×	**0.5 – K** **0.5 – F**	×
90	Normal	1	19	3	5	3	345	1	0	1	0	**G**	×	**0.5 – G** **0.5 – F**	×
91	Normal	1	16	2	3	3	265	1	0	1	0	**G**	×	**G**	×
92	Overheating	1	12	81	32	8	48	1	1	0	1	**∅**		**∅**	
93	Overheating and thermal decomposition involve cellulose	1	10	190	107	19	520	0	2	0	1	**N**	✓	**N**	✓
94	Normal	1	10	2	3	4	235	1	0	1	0	**G**	×	**G**	×
95	Thermal decomposition involve cellulose	1	7	59	56	13	398	0	2	0	1	**N**	✓	**N**	✓
96	Normal	1	5	7	5	29	327	0	1	2	1	**P**	×	**P**	×
97	Overheating	1	4	222	76	9	202	1	2	0	1	**∅**		**∅**	
98	Normal	1	4	3	3	2	178	1	0	0	1	**K**	×	**0.5 – K** **0.5 – F**	×
99	Normal	1	4	2	4	3	242	1	1	1	0	**∅**		**0.5 – G**	×
100	Overheating	0.4	59	1	2	63	273	0	5	2	0	**∅**		**∅**	

Interpretation	Description
A	No fault
B	Partial discharge of low energy density or hydrolysis
C	Partial discharge of high energy density, possible with tracking
D	Coincidental partial discharges and conductor overheating
E	Partial discharge of increasing energy density
F	Low energy discharge : Flashover without power follow through
G	Low energy discharge : Continuos sparking to floating potential
H	High energy discharge : Arc with power follow through
I	Insulated conductor overheating
J	Complex thermal hotspot and conductor overheating
K	Coincidental thermal hotspot and low energy discharge
M	Thermal fault of low temperature range < 150 °C
N	Thermal fault of temperature range 100-200 °C
O	Thermal fault of temperature range 150 –300 °C : Overheating of copper due to eddy currents
P	Thermal fault of temperature range 300-700 °C : Bad contacts/joints (pyrolytic carbon formation) : core and tank circulating currents.
∅	**NOT MATCH WITH ANY GROUP**

Symbol	Description
✓	Correct case
✗	Wrong case

Human Expert Interpretation	Rogers Ratio Interpretation
Normal	A
Arcing	F, G, H
Corona, partial discharge	B, C, D, E
Overheating Low temperature oil breakdown, High temperature oil breakdown Thermal decomposition involve cellulose	I, J, K, M, N, O, P

APPENDIX E

NEWSPAPER CUTTING- THE STAR 13 MARCH

Explosion at TNB sub station

KLANG: A transformer of a transmission main intake sub station at the 7km of Jalan Meru here exploded and caught fire yesterday.

The 10am incident caused a power disruption to about 20,000 consumers in Meru, part of Kapar, Bukit Rajah and part of Klang town.

A Fire and Rescue Department spokesman said two fire engines with 20 personnel were rushed to the scene.

Power was restored in stages within 90 minutes after technical staff turned on the switch gears controlling the ring system for the sub stations.

TNB Chief Operations Officer (Metro) Datuk Samsuddin Sairan said they were still investigating the cause of the explosion.

He estimated damage to cost several hundred thousands of ringgit.

"We are not worried about the cost of damages as all the parts are insured,

"Our main concern was to restore the supply at the soonest possible time," he said.

APPENDIX F

PUBLICATION I

Wan, Yat How and Marzuki Khalid (1999). “Transformer Fault Diagnosis Using Fuzzy Logic Interpretations.” Conference Proceeding of InstrumentAsia99 (CIA99) Technical Symposium. Singapore.

APPENDIX G

PUBLICATION 2

Wan, Yat How and Marzuki Khalid (2000). “ADAPT - An Intelligent Software for the Diagnosis of Power Transformers.” Conference on Intelligent Solutions for Manufacturing Systems in the New Millennium. Kuala Lumpur, Malaysia.