INVESTIGATION OF NUMERICAL TECHNIQUE TO EVALUATE FREQUENCY RESPONSE ANALYSIS (FRA) DATA MEASUREMENT OF AUTO POWER TRANSFORMER

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ABSTRACT

Power and distribution transformers are expensive and important units in electric power networks. Majority of dielectric and mechanical failures in transformers are due to mechanical displacements in the winding structure. Detection of these winding displacements in advance of a dielectric failure can reduce unplanned maintenance costs and provide the possibility to improve system reliability by preventing outages and breakdowns. Frequency Response Analysis (FRA) is a powerful and sensitive diagnostic test technique to evaluate transformer winding displacements by measuring their electrical transfer functions over a wide frequency range. In the past, it has really required trained experts to interpret the FRA test results in a subjective manner to make a judgement as whether the amount of agreement or disagreement between the two or more sets of FRA measurements is significant enough for further testing and inspection of the transformer. Therefore, a quite number of numerical techniques have been proposed to analyze the FRA data such as Standard Deviation (SD), Absolute Sum of Logarithmic Error (ASLE), Correlation Coefficient (CC), and others. Several of the numerical techniques were evaluated for its suitability, reliability and sensitivity for different cases of auto power transformer, 1000 MVA, 400/ 275/ 13 kV HV neutral winding terminations and comparison methods. It is concluded that Absolute Sum of Logarithmic Error (ASLE) is more reliable and sensitive. The ASLE technique should included as an analysing technique in any FRA test to get better interpretation and increase opportunities to provide more objective comparison of FRA test results.

ABSTRAK

Alatubah kuasa dan pembahagian merupakan unit yang mahal dan penting di dalam rangkaian tenaga elektrik. Majoriti kegagalan dielektrik dan mekanikal di dalam alatubah adalah disebabkan perubahan mekanikal di dalam struktur gelung. Pengesanan awal perubahan gelung dapat mengurangkan kos penyelenggaraan tidak terancang dan menyediakan kemungkinan untuk meningkatkan kebolehpercayaan sistem dengan mencegah hentitugas dan kerosakan. Analisis Reaksi Frekuensi (FRA) adalah teknik ujian diagnostik yang amat berkuasa dan sensitif untuk menilai perubahan gelung alatubah dengan mengukur fungsi pemindahan elektrik di dalam julat frekuensi yang luas. Di masa lalu, pakar yang terlatih adalah diperlukan untuk membuat penafsiran hasil ujian FRA secara subjektif dan membuat penilaian sama ada amaun kesamaan dan ketidaksamaan di antara dua atau lebih set data FRA adalah cukup signifikan untuk ujian dan pemeriksaan lebih lanjut ke atas alatubah. Oleh itu, beberapa teknik-teknik berangka telah dicadangkan untuk menganalisa data FRA seperti Sisihan Piawai (SD), Jumlah Kesilapan Logaritma Mutlak (ASLE), Pekali Hubungkait (CC) dan sebagainya. Beberapa teknik berangka telah dinilai untuk kesesuaian, kebolehpercayaan dan kepekaan bagi kes-kes yang berbeza pengubah kuasa automatik, 1000 MVA, 400/275/13 kV kuasa tinggi pada neutral penamatan penggulungan dan kaedah perbandingan dilakukan. Kesimpulan telah dibuat bahawa Teknik Jumlah Kesilapan Logaritma Mutlak (ASLE) adalah lebih boleh berdayaharap dan sensitif. Teknik Jumlah Kesilapan Logaritma Mutlak (ASLE) haruslah dimasukkan sebagai teknik analisis dalam sebarang ujian FRA untuk mendapatkan keputusan penafsiran yang lebih baik dan meningkatkan peluang untuk memberikan perbandingan hasilujian FRA yang lebih objektif.

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LIST OF SYMBOLS AND ABBREVIATIONS

Xi,yi	-	*i*th elements of the reference fingerprints and measured frequency response
N	-	total number of samples in the frequency response
dB	-	decibel
Hz	-	Hertz
Ω	-	Ohm
SCI	-	Short Circuit Impedance
LVI	-	Low Voltage Impulse
FRA	-	Frequency Response Analysis
DGA	-	Dissolved Gases Analysis
SD	-	Standard Deviation
CC	-	Correlation Coefficient
ASLE	-	Absolute Sum of Logarithmic Error
DABS	-	Absolute Average Difference
SFRA	-	Sweep frequency response analysis
IFRA	-	Impulse Frequency Response Analysis
SSE	-	Sum of Squares Error

SSRE - sum squared ratio error

SSMMRE - sum square max min error

FFT - Fast Fourier Transform

LV - Low Voltage

HV - High Voltage

RLC - Resistance, Inductance and Capacitance

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Power transformers are one of the most important items of equipment in electric power system networks. They are one of the main devices in the utility grids. Reliability, power quality, economic cost and even the company image are influenced by the transformers health. Advanced techniques have been developed in recent years in order to improve the transformer life assessment. The main aim is to check the actual health state of a particular transformer in order to predict the break down before it occurs and predict whether need to repair the transformer without open it [1]. There are a quite number of conditions has been the reason for an electrical transformer failure. One of the most severe failures in transformers is winding deformation. Statistics show that winding failures most frequently cause transformer faults (ANSI=IEEE, 1985).

These displacements in the winding maybe the result of transportation damage occurring between the manufacturer and the installation location, short circuit forces imposed on the windings resulting from a low impedance fault occurring close to the transformer and natural effects of aging on the insulating structures used to support the windings. As stated before, the majority of dielectric and mechanical failures in distribution transformers are due to mechanical displacements in the winding structure. Detection of these winding displacements in advance of a dielectric failure can reduce unplanned maintenance costs and provide the possibility to improve system reliability by preventing outages and breakdowns.

The main methods on detection of transformer winding displacement are Short Circuit Impedance Measurement (SCI), Low Voltage Impulse Method (LVI), and Frequency Response Analysis Method (FRA). The Short Circuit Impedance Measurement is not widely used on site because its sensitivity is low and the hidden trouble can not be found effectively. On the hand, the sensitivity of LVI and FRA is high, their principles are similar. However, the parameter of single impulse voltage source used in LVI can hardly be the same all the time, and therefore the FRA is the most suitable method on site.

Frequency response analysis (FRA) method is more and more frequently being used for identification of transformer windings as a main diagnostic tool. FRA is a powerful and sensitive diagnostic test technique to winding displacements by measuring their electrical transfer functions over a wide frequency range. It has grown in usage over the last decade and is now being standardized by both IEEE and CIGRE. The FRA technique can help maintenance personnel identify suspect transformers and enabling them to take those transformers out of service before failure.

1.2 Problem Statement

The challenge for a consistent electricity supply has increased during the past few decades such that fault-free operation of electrical power system is necessary. The reliability of power system depends on trouble-free electrical equipment used in the power electrical substations. Transformer (Figure 1.1) is one of the most critical and costly equipments used in the electrical power network.

Figure 1.1 One of transformer owned by Tenaga Nasional Berhad

The breakdown of transformer can cause interruption of power supply and consequences in loss of revenue both to the electricity companies and society. Electricity companies are looking for ways to assess the actual condition of their transformers, with the aim to minimize the risk of failures and to avoid forced outages on strategically important units.

Several diagnostic techniques are available for monitoring of several parameters, which could show the condition or the ageing of the transformer insulation due to various phenomena. Amongst the commonly employed method include dissolved gases analysis (DGA) (Figure 1.2), furanic compound analysis, power factor measurement, partial discharge measurement (Figure 1.3), and others.

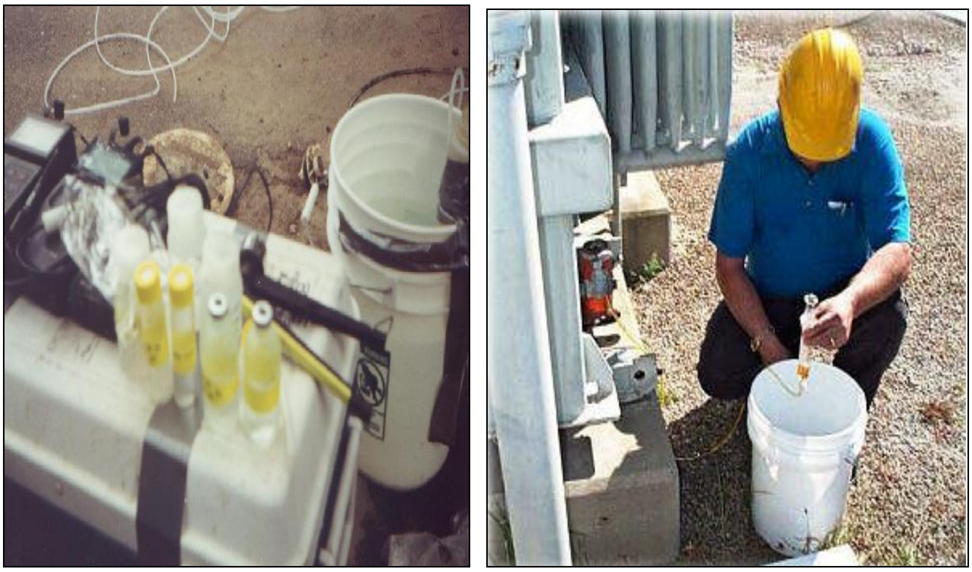


Figure 1.2 On site - DGA test

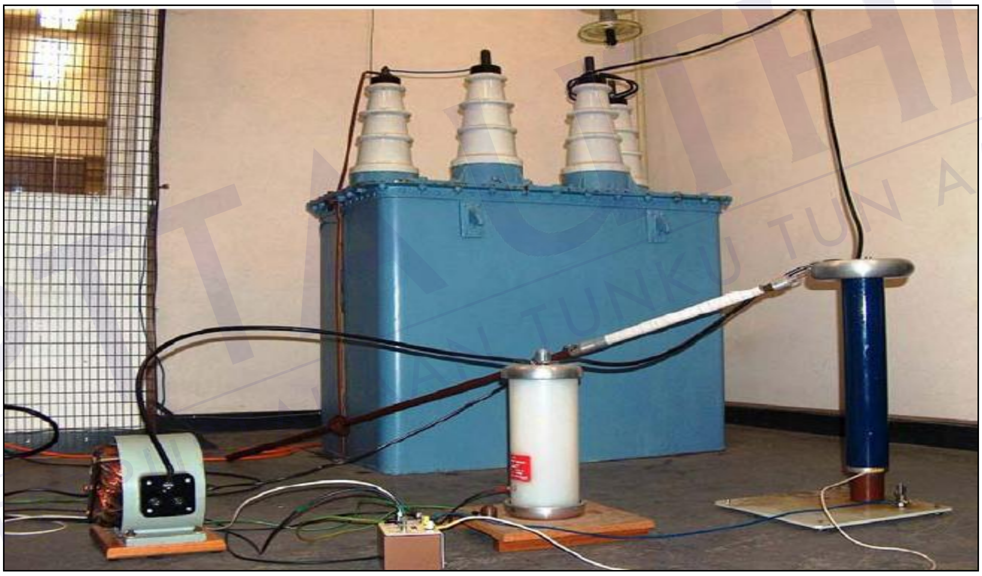


Figure 1.3 On lab - partial discharge measurement

In addition to the insulation degradation, transformers also experience from mechanical damage from very large electromagnetic forces arising during short circuits or over voltages in power system. It is expected that a transformer will experience and survive a number of short circuits during its service life, but sooner or later one such event will cause some slight winding movement, and the ability of the transformer to survive further short circuits will then be severely reduced. Besides, significant shrinkage can occur leading to reduction in clamping pressure and short-circuit strength.

Such problems can cause catastrophic failures when undetected or not rectified. Visual inspections are expensive and time consuming because of the oil handling required and are very often inconclusive. Conventional condition monitoring techniques such as DGA are unlikely to be able to detect such damage until it develops into a dielectric or thermal fault. A specialized technique is thus required for the monitoring and assessment of mechanical condition of the transformers.

Now, one of the methods which are becoming an increasingly important condition monitoring tool is the Frequency Response Analysis (FRA) technique. This method involves measuring the transfer function of the transformer windings as a function of frequency. Any disruption of the winding arrangement will alter the distributed network of resistances, capacitances and inductances locally which will result in changes to the transfer function response.

Although FRA is becoming as a powerful transformer windings displacement diagnostic tool but it still do not have a general guideline as such for interpreting frequency response of transformer. Some manufacturing industries use their own procedure to interpret the FRA data and it was reported that some interpretations of FRA data were not clear and the failure criteria were uncertain.

Therefore, a quite number of numerical techniques have been proposed to analyze the FRA measurement such as Standard Deviation (SD), Spectrum Deviation, Correlation Coefficient (CC), Absolute Sum of Logarithmic Error (ASLE), Absolute Average Difference (DABS) and others. These numerical techniques will be evaluated for its suitability, reliability and sensitivity for different cases of power transformer winding faults and comparison methods.

1.3 Objectives

The objectives of this research are:

1. To evaluate the performance of numerical techniques.
2. To analyze FRA data measurement of Auto power transformer.
3. To conclude which technique is more reliable and sensitive.

1.4 Project Scope

There are two main limitations for this project.

(i) Parameter

- Three numerical techniques were used such as Standard Deviation (SD), Absolute Sum of Logarithmic Error (ASLE) and Correlation Coefficient (CC)
- The FRA data 1000 MVA, 400/ 275 / 13 kV auto transformer from utility transformer
- Divided into three group of frequency
  (a) 1kHz to 10kHz for low frequency
  (b) 10kHz to 100kHz for medium frequency
  (c) 100kHz to 1MHz for high frequency

(ii) Software

- MATLAB to plot the graph from FRA data.
- Microsoft Excel to calculate the value of numerical techniques

CHAPTER 2

LITERATURE REVIEW

2.1 Transformer

ANSI/IEEE defines a transformer as a static electrical device, involving no continuously moving parts, used in the electric power systems to transfer power between circuits through the use of electromagnetic induction. Transformer is the heart of a power distribution system. Since the early stages of domestic electricity use the transformer has formed the backbone of the electrical distribution system. Its main purpose is to convert voltage at the generating end to transmission voltages and then to convert it back at the receiving end for utilization voltages.

The transformer usually consists of two or more insulated windings on a common iron core. If an alternating current flows in a primary winding of the transformer, a magnetic field exists around the conductor. If a secondary winding is placed in the field created by the first winding, then a voltage is generated into the second winding.

2.1.1 Transformer History

The principle of electromagnetism and the transformer was demonstrated by Michael Faraday in 1831. In the experiment, a voltage pulse was induced across the secondary terminals of his experimental apparatus by interrupting the flow of direct current. So, he concluded that large currents could be transformed into small currents and the other way around.

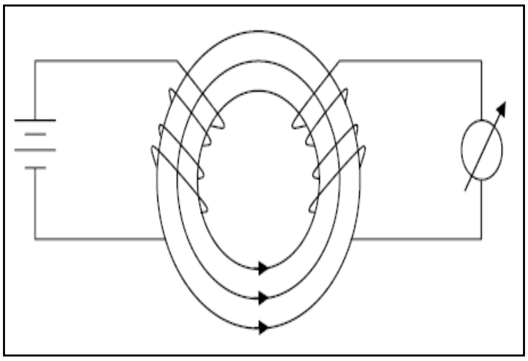


Figure 2.1 Faraday's experimental apparatus [19]

In 1886, George Westinghouse built the first long-distance alternating-current electric lighting system in Great Barrington, MA and he realized that electric power could only be delivered over distances by transmitting at a higher voltage and then reducing the voltage at the location of the load. He purchased U.S. patent rights to the transformer developed by Gaulard and Gibbs.

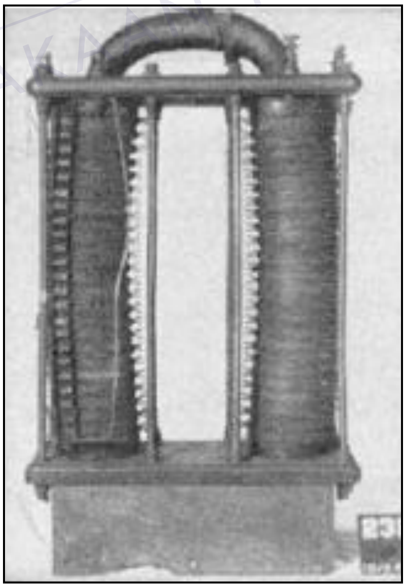
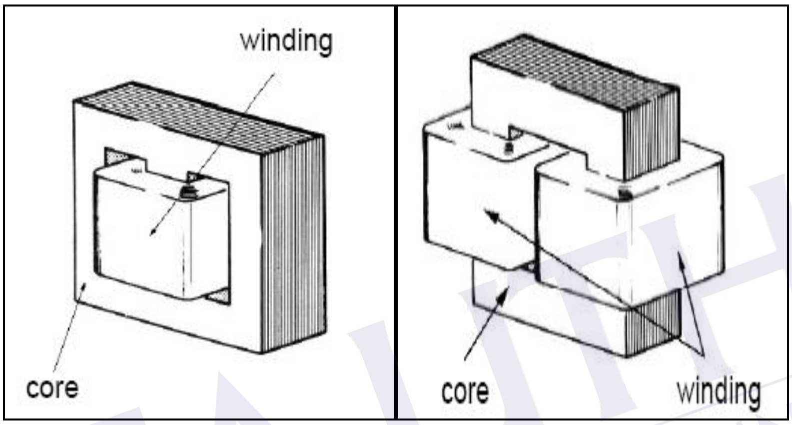


Figure 2.2 Gaulard and Gibbs transformer [19]

2.1.2 Type of Transformer

There are two basic types of transformers categorized by their winding and core configuration:-

a) Shell type
b) Core type



(a) (b)

Figure 2.3 (a) Shell type (b) Core type [19]

2.1.3 Insulation Systems

Insulation system is one of the most important aspects of the transformer design. It can be categorized into major and minor insulation:-

(a) Major - insulation between windings, between windings and limb / yoke, and between high voltages leads and ground.
(b) Minor - internal insulation within the windings, namely, inter-turn and inter-disk insulation.

And there are two types of insulation materials:-

(a) Solid – kraft paper, pressboard
(b) Liquids – mineral oil, silicone oil

2.2 Transformer Failures and Problems

Transformer failure can occur as a result of different causes and conditions. Generally, transformer failures can be defined as follows:-

- any forced outage due to transformer damage in service (e.g., winding damage, tap-changer failure)
- Trouble that requires removal of the transformer for return to a repair facility, or which requires extensive field repair (e.g., excessive gas production, high moisture levels).

Transformer failures can be broadly categorized as electrical, mechanical, or thermal [2]. The cause of a failure can be internal or external. Table 2.1 lists typical causes of failures. In addition to failures in the main tank, failures can also occur in the bushings, in the tap changers, or in the transformer accessories.

Table 2.1 Typical Causes of Transformer Failures

Internal	**External**
Insulation deterioration	Lightning strikes
Loss of winding clamping	System switching operations
Overheating	System overload
Oxygen	System faults (short circuit)
Solid contamination in the insulating oil	
Partial discharge	
Design &manufacture defects	
Winding resonance	

Statistics show that winding failures most frequently cause transformer faults. Insulation deterioration, often the result of moisture, overheating, vibration, voltage surges, and mechanical stress created during transformer through faults, is the major reason for winding failure. Voltage regulating load tap changers, when supplied, rank as the second most likely cause of a transformer fault. Tap changer failures can be caused by a malfunction of the mechanical switching mechanism, high resistance load contacts, insulation tracking, overheating, or contamination of the insulating oil.

Transformer bushings are the third most likely cause of failure. General aging, contamination, cracking, internal moisture, and loss of oil can all cause a bushing to fail. Two other possible reasons are vandalism and animals that externally flash over the bushing. Transformer core problems have been attributed to core insulation failure, an open ground strap or shorted laminations. Other miscellaneous failures have been caused by current transformers, oil leakage due to inadequate tank welds, oil contamination from metal particles, overloads and overvoltage.

The causes of transformer failure can be summarized as shown in Table 2.2.

Table 2.2 Causes of transformer failure

Type of transformer failure	**Causes**
Winding Displacement	• Transportation • Short circuit • Natural effects of aging (insulation deterioration)
Tap changer	• Mechanical malfunction • Overheating • Contamination of insulating oil
Bushing	• Aging • Internal moisture • Loss of oil • Flashover (animal & vandalism)
Other	• Core • Current transformer • Oil leakage • Oil contamination • Overload • Overvoltage

In order to maximize the lifetime and efficiency of a transformer, it is important to be aware of possible faults that may occur and to know how to detect them early [3]. Regular monitoring, tests and maintenance can make it possible to detect problems before much damage has been done [4]. The following tests are routinely conducted in the field on the transformer:

a) IR test

b) AC or DC hi-pot test (optional)

c) Insulation PF test

d) Transformer Turns Ratio (TTR) test

e) Polarity test

f) Excitation current test

g) Induced potential test (optional)

h) Insulating fluid dielectric tests

i) Dissolved gas analysis (DGA) tests

j) Polarization recovery voltage test

k) Transformer core ground test

l) DC winding resistance

m) Frequency response analysis (FRA)

2.3 Previous Research

The first and a very important step in any project is the accumulation of knowledge on subjects relating to the proposed research study. In this stage, important information on FRA including the theoretical aspect and concept, measurement principle and technique, data analysis method and interpretation should be obtained from various resources, such as technical papers, journals and reference books. This activity is very important as it will provide knowledge, guidance and resources during the implementation of the project.

2.3.1 Application of numerical evaluation techniques for interpreting frequency response measurements in power transformers

This paper wrote by P.M. Nirgude, D. Ashokraju1, A.D. Rajkumar and B.P. Singh (2008). This work reported on discussion about numerical criteria based on evaluation techniques. This techniques can be apply for those who not familiar with interpreting the FRA results. The techniques mentioned above are useful for interpreting frequency responses even in situations when a reference fingerprint was not available .The experimental studies were conducted on two test transformers for axial and radial displacements, and additionally two sets of identical substation transformers. By evaluating correlation coefficient (CC), standard deviation (SD) and absolute sum of logarithmic error (ASLE) techniques, it is possible to discriminate between defective and non-defective windings.

The results concluded that ASLE and SD of comparable frequency responses clearly discriminate the defective winding. The methods have shown enough sensitivity to detect the faulty winding. However, the exact location of the abnormality is not defined. Without reference fingerprints, it is possible to diagnose winding displacement/deformation using numerical methods by considering tolerance limit for both symmetrical winding and sister unit comparison approach.

2.3.2 Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers

This paper was done by J.R Secue and E. Mombello in 2008. This paper presents a survey on the alternatives in the measurement techniques and interpretation of SFRA measurements, describing some sources of uncertainty in applying this methodology. SFRA as a diagnostic technique must integrate both the off-line measurements and the interpretation of the data in order to provide an assessment of the condition of the windings. However, guidelines for the measurement and record interpretation are not available. So, the evaluation is presently done by experts in the topic through the visual inspection or with the help of statistical parameters such as the correlation coefficient (CC) and the standard deviation.

The conclusion was that CC is a useful statistical parameter, while standard deviation is an unreliable comparison parameter. But, the authors state that CC is not sensitive for detecting changes in the frequency response characterized by a similar shape but having a constant difference in magnitude, and that an undesirable overestimation of the parameter standard deviation takes place when the order of magnitude of the two responses analyzed differs not as a consequence of any fault but as a consequence of the slight shift of a peak, which is normal in this type of measurement. Other parameters such as: sum of squares error (SSE), sum squared ratio error (SSRE), sum square max–min error (SSMMRE), and absolute sum of logarithmic error (ASLE) were proposed by the authors in order to correct these undesirable characteristics of the CC and standard deviation. However, most of them, excepting ASLE, have undesirable numerical disadvantages. ASLE was presented as the most reliable parameter which was designed to make the fully log-scaled comparison in the magnitude frequency response; its application considers a previous process of interpolation proposed by the authors.

2.3.3 Winding Movement in Power Transformers: A Comparison of FRA Measurement Connection Method

This paper wrote by J.A.S.B Jayasinghe, Z.D. Wang, P.N. Jarman and A.W. Darwin (2006). In this paper, a simulation model of a 132/11 kV, 30 MVA transformer was used. The investigations were carried out on the sensitivity of three different connections; end to end voltage ratios, input admittance and transfer voltage ratio to three different types of winding movement such as axial displacement, forced buckling and axial bending.

The results show transfer function ratio connection has the best sensitivity to axial displacement and forced buckling while end to end ratio has best sensitivity towards axial bending. The researchers concluded that no single FRA connection scheme is the best for detecting all three types of winding movement but they recommended that both end to end and transfer function ratio measurements be made to cover the major types of winding movement.

2.3.4 Frequency Response Analysis (FRA) for Diagnosis of Power Transformers

This paper wrote by Suwarno and F. Donald from School of Electrical Engineering and Informatics, Bandung, Indonesia. In this experiment, they did the FRA measurement using Omicron and applied it to the three phase transformer of 6000/220 V, 100 kVA. The equivalent circuit having of R, L and C were calculated at low, medium and high frequency and tested in four kinds of sample condition such as normal condition, inter short circuit condition, displacement of coil disk in axial position and radial deformation of coil (buckling).

The output from this experiment, they could conclude that short circuit greatly affected at the low frequency component while axial displacement of coils slightly affected the medium frequency component. Buckling and short circuit significantly affected the low and medium frequency components.

2.3.5 Interpretation of Transformer FRA Measurement Results using winding Equivalent Circuit Modelling Technique

This journal wrote by D.M Sofian, Z.D Wang and P. Jarman from School of Electrical Engineering & Electronic, The University of Manchester, UK. They studied a technique which converts the FRA measurement result into a transformer equivalent circuit model. The healthy and deformed FRA results from laboratory and site examples are converted into the transformer equivalent circuit to determine the circuit components affected by the deformation.

The data points of the FRA measurement result are first condensed into a transfer function and then converted into the partial fraction format by using the certain formulas. This is possible by converting the z domain transfer function into s domain transfer function using bilinear method and equating the equation the equations into the corresponding branches represented by the admittance equation.

Then, the winding circuit technique is initially applied to FRA measurement results obtained from the laboratory interleaved winding simulated with axial displacement and broken axial clamping.

The equivalent circuit from healthy and faulty transformers is compared and the differences reflect, in a relatively simple manner, the physical changes to the actual transformer winding. The researchers suggest that the further investigation need to be carried out to validate the technique but it appears to provide a practical way of identifying and classifying winding deformation.

2.4 Comparison between the previous researches.

Table 2.3 showed the comparison between methods and outcomes from previous researchers.

Table 2.3 Comparison previous researches

Journal	Method	Outcome
Application of numerical evaluation techniques for interpreting frequency response measurements in power transformers	1. The experimental studies were conducted on two test transformers for axial and radial displacements, and additionally two sets of identical substation transformers. 2. Evaluating correlation coefficient (CC), standard deviation and absolute sum of logarithmic error (ASLE) techniques to discriminate between defective and non-defective windings.	1. The results concluded that ASLE and SD of comparable frequency responses clearly discriminate the defective winding. 2. However, the exact location of the abnormality is not defined.
Winding Movement in Power Transformers: A Comparison of FRA Measurement Connection Methods	1. 132/11 kV, 30 MVA 2. Three different FRA measurement connection end to end voltage ratios, input admittance and transfer voltage ratio. 3. Investigations are carried out on the sensitivity of these connections to three different types of winding movement; axial displacement, forced buckling and axial bending.	1. A correlation exits between the FRA measurements provided that the HV neutral is grounded. 2. Transfer function ratio connection has the best sensitivity to axial displacement and forced buckling. 3. End to end ratio has best sensitivity towards axial bending. 4. No single FRA connection scheme is the best for detecting all three types of winding movement.

Table 2.3 Continue

Journal	Method	Outcome
Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers	1. A survey on the alternatives in the measurement techniques and interpretation of SFRA measurements. 2. However, guidelines for the measurement and record interpretation are not available. 3. So, the evaluation is presently done by experts in the topic through the visual inspection or with the help of statistical parameters such as the correlation coefficient (CC) and the standard deviation. 4. Other parameters such as sum of squares error (SSE), sum squared ratio error (SSRE), sum square max–min error (SSMMRE), and absolute sum of logarithmic error (ASLE) were proposed in order to correct these undesirable characteristics of the CC and standard deviation.	1. The conclusion was that CC is a useful statistical parameter, while standard deviation is an unreliable comparison parameter. 2. But, that CC is not sensitive for detecting changes in the frequency response characterized 3. However, most of them, excepting ASLE, have undesirable numerical disadvantages. 4. ASLE was presented as the most reliable parameter which was designed to make the fully log-scaled comparison in the magnitude frequency response; its application considers a previous process of interpolation.
Frequency Response Analysis (FRA) for Diagnosis of Power Transformers	1. 6000/220 V, 100 kVA 2. R, L and C were calculated at low, medium and high frequency. 3. Four kinds of sample condition were conducted; normal condition, inter short circuit condition, displacement of coil disk in axial position and radial deformation of coil (buckling).	1. Short circuit greatly affected at the low frequency component. 2. Axial displacement of coils slightly affected the medium frequency component. 3. Buckling and short circuit significantly affected the low and medium frequency components

Table 2.3 Continue

Journal	Method	Outcome
Interpretation of Transformer FRA Measurement Results using Winding Equivalent Circuit Modelling Technique	1. Studied a technique which converts the FRA measurement result into a transformer equivalent circuit model. 2. The healthy and deformed FRA results are converted into the transformer equivalent circuit to determine the circuit components affected by the deformation. 3. The data points of the FRA measurement result are first condensed into a transfer function and then converted into the partial fraction format. 4. Then, the winding circuit technique is initially applied to FRA measurement results obtained from the laboratory interleaved winding simulated with axial displacement and broken axial clamping.	1. The equivalent circuit from healthy and faulty transformers is compared and the differences reflect, in a relatively simple manner, the physical changes to the actual transformer winding. 2. The researchers suggest that the further investigation need to be carried out to validate the technique but it appears to provide a practical way of identifying and classifying winding deformation.

CHAPTER 3

METHODOLGY

3.1 Process Architecture

Figure 3.1 is a flowchart of the whole study which represents all steps involve while doing this project. A good plan is important in order to achieve the target within the period given. To complete the study, a good method needs to be developing first in order to make sure there was no problems occur during this project's study. The informations are gathered from previous thesis, IEEE papers, book in library, surf web in internet and referring to journals.

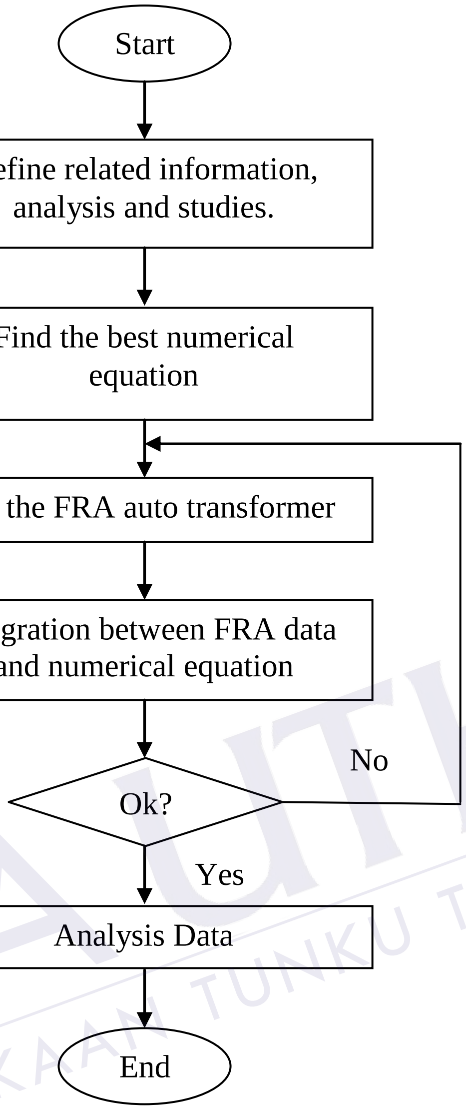


Figure 3.1 Flow chart of Study Implementation

3.2 General Description of Frequency Response Analysis (FRA)

With the increasing age of the population of assets, complex designs and changing expectations, organizations are making efforts to assess the internal condition of the equipment while in service before catastrophic failures can take place to ensure higher availability and reliability. The challenges faced by maintenance staffs are as follows:-

a) To select the most appropriate techniques to deal with each type of failure process in order to fulfil all the expectations of the owners of the assets, the users of the assets and of society as whole.
b) In the most cost-effective and enduring fashion.
c) With the active support and co-operation of all involved.

Maintenance management is also responding to changing expectations. Since the 1930's, the evolution of maintenance can be traced through three generation to capture growing expectations of the industries and more importantly maintenance staffs.

3.3 History of FRA

Frequency Response Analysis (FRA) has been developed over the years since its introduction in its 1960's [6]. It initially used the impulse measurement technique and software was used to transform results from the time domain to frequency domain. In the 1970's Ontario Hydro pioneered frequency response by injecting a sinusoidal signal and measured the frequency response directly.

In the 1980's National Grid Company (UK) refined the technique by first using the impulse method but soon the sweep method was employed as it was found to be better suited for site work and gave better high frequency results. The 1990's saw the introduction of the first commercially built systems to be used on site. Presently there are a number of worldwide users that use the sweep and impulse method.

3.3.1 Brief History

Since the pioneering work of Dick and Erven at Ontario Hydro in the late 1970s, FRA has been applied to power transformers to investigate mechanical integrity. The brief history of FRA showed in Table 3.1.

Table 3.1 Brief History

Year	Descriptions
1960	Low Voltage Impulse Method (LVI). First proposed by W. Lech & L. Tyminski in Poland for detecting transformer winding deformation.
1966	Results Published: W. Lech and L. Tyminski, "Detecting transformer winding damage—the low voltage impulse method," Electric. Review, no. 18, ERA, UK. The method was used by Dr. Alexandr Dorbishevsky in former USSR and within Bonneville Power Administration, United States (Eldon Rogers)
1976	"Frequency Domain Analysis of Responses From L.V.I. Testing of Power Transformers" Presented by A.G. Richenbacher at the 43rd Doble International Client Conference
1978	E. P. Dick and C. C. Erven, "Transformer diagnostic testing by frequency response analysis", IEEE Trans. Power App. Syst., vol. PAS-97, no. 6, pp. 2144–2153
1978	E. P. Dick and C. C. Erven , FRA test developed at Ontario Hydro. Evaluated LVI and SFRA and contributed to further knowledge of their use for transformer diagnostics
1980's	Further research carried out by Central Electricity Generating Board in UK
1988	Malewski, R., Poulin, B., "Impulse Testing of Power Transformers Using the Transfer Function Method", IEEE Transactions, Vol. PWRD-3, 1988, No. 2, pp. 476-489. New ideas on digital recording of High Voltage impulse tests and analysis by comparison of transfer functions
1988 – 1990's	Proving trials by European utilities, the technology cascades internationally via CIGRE, EuroDoble and many other conferences and technical meetings
1992	Leibfried, T.; Feser, K.; Hengge, 6.; Kemm, P."Diagnose des Isoaltionszustandes von Transformatoren mit Hilfe der Transferfunktion". ETG-FachberichtNr. 40, VDEVerlag, Brought the use of transfer function analysis of HV pulses to three phase transformers. (Later publications at IEEE)
1998	Moreau, O., Guillot, Y., "SUMER: A Software For Overvoltage Surges Computation Inside Transformers", Int. Conf. On Electrical Machines, 1998, pp. 965-970. Simulation software to aid interpretation of differences between transfer functions
2002	S. Ryder, "Methods for comparing frequency response analysis measurements," in Proc. 2002 IEEE Int. Symp. Electrical Insulation, Boston, MA, 2002, pp. 187-190. Comparison between two statistical methods to compare FRA response curves
2003	Coffeen, L.; Britton, J.; Rickmann, J; "A new technique to detect winding displacements in power transformers using frequency response analysis", Power Tech Conference Proceedings, 2003 IEEE Bologna, Volume 2, 23-26 June 2003 Page(s):7 pp. Vol.2. Utilizes statistical techniques (on LVI measured data) when comparing FRA response curves. The objective is to calculate quantitative indicators to indicate fault situations

Table 3.1 Continue

2004	First SFRA standard, "Frequency Response Analysis on Winding Deformation of Power Transformers", DL/T 911-2004, is published by The Electric Power Industry Standard of People's Republic of China
2008	CIGRE report 342, "Mechanical-Condition Assessment of Transformer Windings Using Frequency Response Analysis (FRA)" is published
1991 to present	Results & Case Studies published and presented, validating the FRA method

3.3.2 Frequency Response Analysis

Frequency response analysis (FRA) method is more and more frequently being used for identification of transformer windings as a main diagnostic tool [2] and [5]. FRA is a powerful and sensitive diagnostic test technique to evaluate power transformer winding displacements by measuring their electrical transfer functions over a wide frequency range. It has grown in usage over the last decade and is now being standardized by both IEEE and CIGRE.

The FRA technique can help maintenance personnel identify suspect transformers and enabling them to take those transformers out of service before failure [2]. The loss of mechanical integrity in the form of winding deformation and core displacement in transformers can be attributed to the large electromechanical forces due to fault currents, winding shrinkage causing the release of the clamping pressure and during transformer transportation and relocation. These winding deformation and core displacement if not detected early will typically manifest into a dielectric or thermal fault.

This type of fault is irreversible with the only remedy been rewinding of the phase or a complete replacement of the transformer. It is therefore imperative to check the mechanical integrity of aging transformers periodically and particularly after a short circuit event to provide early warning of impending failure. Hence an early warning detection technique of such phenomena is essential. The transformer is considered to be a complex network of RLC components [2]. The contributions to this complex mesh of RLC circuit are from the resistance of the copper winding; inductance of winding coils and capacitance from the insulation layers between coils, between winding, between winding and core, between core and tank, between tank and winding. A simplified equivalent circuit with lumped RLC components of transformer is illustrated in Figure 3.2.

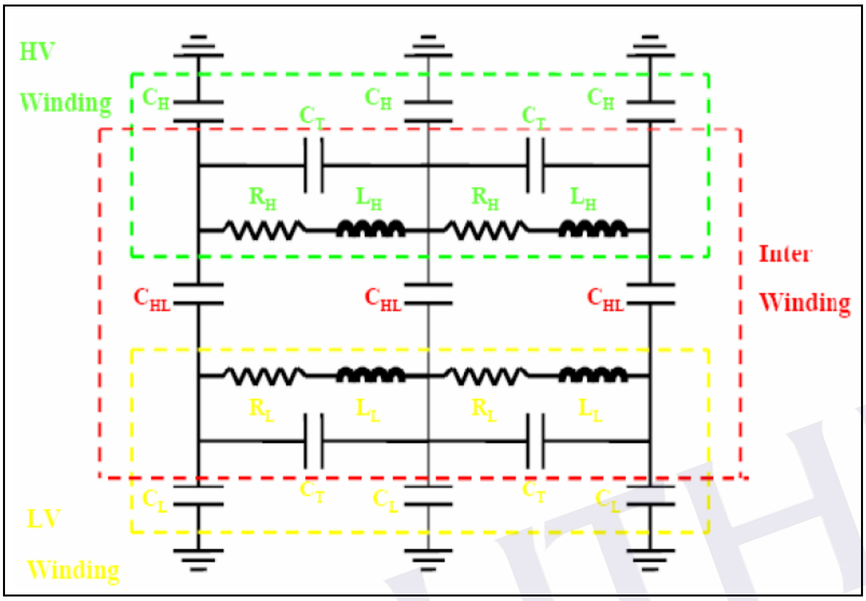


Figure 3.2 Simplified equivalent circuits with lumped RLC components [8]

Any form of physical damage to the transformer results in the changes of this RLC network. These changes are what we are looking for and employ frequency response to highlight these small changes in the RLC network within the transformer.

Frequency Response is performed by applying a low voltage signal of varying frequencies to the transformer windings and measurement both the input and output signals. The ratio of these two signals gives the required response. The ratio is called the transfer function of the transformer from which both the magnitude and phase can be obtained. For different frequencies the RLC network offers different impedance paths. Hence, the transfer function at each frequency is a measure of the effective impedance of the RLC network of the transformer. Any geometrical deformation changes the RLC network, which in turn changes the transfer function at different frequencies and hence highlights the area of concern.

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