The University of Western Australia

School of Mechanical and Chemical Engineering

A Study of Winding Failure Modes in Laboratory Scale Transformers

Li Zhu

B.E. Mechanical Engineering

Submitted for the degree of Master by Research in Engineering

Statement of Originality

The work in this thesis contains no material that has been submitted for any other degree or institution. To the best of the author's knowledge, this thesis contains no material previously published or written by another person, except where references are made.

Li Zhu

March, 2011

Abstract

The population of power transformers in industry is aging. Failures of power transformers induce catastrophic consequences like fire, electric system outages or even loss of life. Therefore, in the past few years, researchers and industry people have been focussed on developing methods to better understand the risk/ life assessment of power transformers.

This project develops and safely conducts laboratory scale test procedures to investigate the behaviours and effects of specific winding failure modes in laboratory scale transformers. The aims of this project are to develop and test process to

(1) Initiate specific winding failures in a safe and repeatable manner in the laboratory,

(2) Observe the behaviour of the transformer failures,

(3) Explore the influence of environmental factors that may accelerate the failure progression,

(4) Observe the behaviour of the tested transformer under different conditions.

The results show the effect of time on the winding temperatures change when the transformer is overloaded. A thermal model of the heat transfer of transformer windings is developed. By monitoring the temperature of the winding surface and the current through the windings, the hot spot temperature can be calculated. Before the hot spot temperature reaches too high and generate an overheating or short circuit failure, actions can be taken to prevent losses of transformers.

Transformer vibration is measured and the results show that at low frequencies, the vibration result of a core-loosened transformer is not significantly different from that of a healthy one. At high frequencies, the vibration result of the transformer with core loosened has more harmonics than that of a healthy one. This appearance of additional harmonics is a potential criterion to identify the core-looseness failure of a transformer.

Acknowledgements

Associate Professor Melinda Hodkiewicz, School of Mechanical Engineering;

I owned my deepest gratitude to my coordinating supervisor, Associate Professor Melinda Hodkiewicz. This thesis would not have been possible without the help from her. Melinda gave me not only the supervision of my research work but also how to deal with problems and stress of research life. There were thousands of times I thought about giving up during my study, she was always there encouraging and supporting me. I am indebted to her for all her kind help.

Winthrop Professor Jie Pan, School of Mechanical Engineering;

I would like to show my gratitude to my co-supervisor Professor Jie Pan. His generous help with my housing problem gave me an easy start of my research life in the University of Western Australia. He also provided me with professional and valuable guidance in every stage of this thesis writing. I saw his enthusiastic passion of research and rigorous academic observation during my study. It encouraged me in my thesis writing and will influence my future life.

I would like to thank the CRC for Engineering Asset Management for the CIEAM Scholarship they provide to me. I am also grateful to all the members of Acoustic and Vibration Team of Mechanical Engineering of UWA. Their kind and unreserved help with all my experiments and study of vibration made my thesis reach this present form. It is an honour for me to thank the technical stuff of the School of Mechanical Engineering. With their patience and cooperation, I completed my lab work of this thesis.

Finally yet importantly, I would like to thank my parents and all my friends. For these years, they gave me absolute support and completely understanding for my study. I regard this time of study as treasure of my life.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Acc: Acceleration

AT: Ambient Temperature.

BBN: Bayesian Belief Network

CBM: Condition Based Maintenance

CIGRE: Conference Internationale des Grandes Reseaux Electriques

CM: Condition Monitoring

DGA: Dissolved Gas Analysis

DP: Degree of Polymerization

FMEA: Failure Modes and Effect Analysis

FRA: Frequency Response Analysis

Ip: Primary Current

Is: Secondary Current

MCRF: Mean Cumulative Repair Function

OLTC: On-load Tap Changer

PD: Partial Discharge

PT: Power Transformer

PVC: Polyvinyl Chloride

RCM: Reliability Centred Maintenance

RMS: Root-Mean-Square

RVM: Recovery Voltage Measurement

Tp: Temperature of Primary Winding

Ts: Temperature of Secondary Winding

Vi: Input Voltage

Vo: Output Voltage

Chapter 1 Introduction

1.1 Aims of the Research

Power transformers are essential components of electric power systems. They are static devices that transfer electrical energy from one circuit to another through inductively coupled conductors- the transformers' windings. Effective detection of the transformers' failure mode has long been the focus in the research and development of power delivery equipment. The focus of UWA transformer team is to develop new methods to detect winding and core failures of power transformers using transformers' vibration signature. This project develops laboratory scale test procedures to investigate the behaviours and effects of specific winding failure modes in power transformers. The results of this will support a larger project to develop a causal model relating degradation influences and remaining useful life.

The specific aims of this project are to develop and test processes to

(1) Initiate specific winding failures in a safe and repeatable manner in the laboratory,

(2) Observe the behaviour of the transformer failures,

(3) Explore the influence of environmental factors that may accelerate the failure progression, and

(4) Observe the behaviour of the tested transformer under different conditions.

1.2 Project Outcomes

There are three main outcomes for this project.

(1) Failure modes for overheating, short circuit and core deformation have been generated in a safe and repeatable manner in the laboratory.

(2) Factors that affect the performance of a power transformer have been observed.

(3) Models for overheating, short circuit and core deformation have been developed.

These results will be used to provide a basic understanding of how deterioration of small transformers are influenced by operating environment, which will be helpful to those, involved in condition assessment of transformer conditions and predicting their remnant life.

1.3 Scope of the Thesis

Chapter 2 is a literature review. It introduces the significance and different types of power transformers. The outcome of a failure mode and effects analysis (FMEA) method for power transformers is presented. It also reviews current methods used in industry to detect and diagnose winding and core failures. It summarizes condition-monitoring techniques on transformer winding and core failures.

Chapter 3 describes the development of methods to create and observe failure modes of power transformers in the laboratory. The FMEA done in Chapter 2 defines overheating, short circuit, deformation of winding and core as the specific failure modes of interest. Overloading test simulates the overheating and short circuit failure modes. Removing several pieces of transformer core simulates the situation when the core is loosened and deformed.

Chapter 4 describes the test setups and observations of the transformer failure modes. All the test rig, process and test results are presented in this part. It includes the changes of all indicators (voltage, current, winding temperature and vibration accelerometer) at different ambient temperatures.

Chapter 5 discusses the observations based on the previous test results. The experimental results are used to test and validate a transfer function model. A thermal model of transformer windings is built to illustrate the heat distribution of the windings. The comparison of vibration results of a healthy transformer and one with 5-10 pieces of core removed is also analysed in this chapter.

Chapter 6 describes the conclusions from the thesis and the future work in this project. It concludes the work done in this thesis and shows the future direction and the final aims and expected outcomes of the project.

1.4 Significance of the Thesis

This thesis originally identifies failure modes, causes and effects of power transformers. It focuses the main failures of power transformers and replicates three failure modes: overheating, short circuit and core deformation on a laboratory scale transformer. It develops models for the three failure modes for the laboratory scale transformer.

The overloading test results show the effect of time on the winding temperatures when the transformer was overloaded. The thesis thus builds a thermal model of the heat transfer of transformer windings. It is a reliable, non-contact method to prevent overheating and short circuit occurring. The vibration test results show the core looseness and subsequent transformer structure change made the vibration level changes. The appearance of additional harmonics is a potential criterion to identify the core-looseness failure of a transformer. By monitoring these parameters, we can diagnose transformer failures like overheating, short circuit and core deformation.

The main findings of the thesis give clear ideas of the effects of change of ambient temperature, the overloading condition and change of the structure of transformer on the transformer performance. These criteria are applicable in power transformers since the three failure modes studied in this thesis are concluded from the failure mode and effect analysis of power transformers. In the condition monitoring of power transformers, considering these factors and properly monitoring these factors in power transformers could effectively prevent such failures happen and eliminate the cost of maintenance hence. That is the contribution of this thesis to the large commercial power transformers.

Chapter 2 Literature Review

2.1 Power Transformers

The basic function of power transformers is to transfer the electrical energy. We know that the transmission of electric power is most efficient at high voltages as the energy loss is proportional to the square of current, but the use of it is best at low voltages. Considering the distances between generators and households and industries, it is essential to covert electricity to high voltage and low current at the generating end for transmission and then converts it to low voltage and high current at the receiving end. From this point of view, power transformers play an essential role in electric power transmission.

Power transformers have different classifications usually by voltage range and insulation medium. Voltage/ current ratings include

1. Small power transformers: up to 7500kVA,

2. Medium power transformers: 7500kVA to 100MVA,

3. Large power transformers: 100MVA and above.

Based on the insulation medium, transformers are classified into three categories:

1. Oil-immersed power transformers,

2. Dry type power transformers,

3. Fluid filled power transformers.

The dry type power transformer has the simplest construction. It consists of a silicone steel core surrounded by primary and secondary windings. Figure 2.1-1 shows a model of a dry type power transformer. Two coils are wound on a steel core.

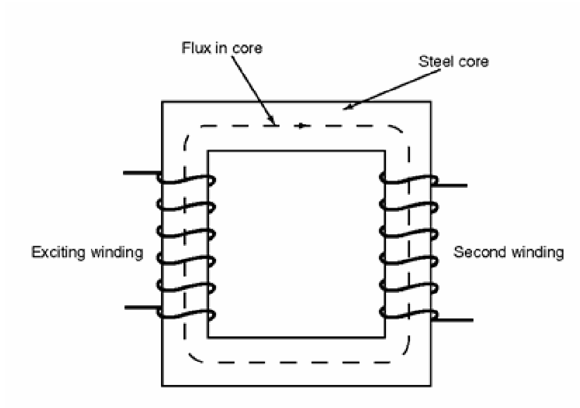


Figure 2.1-1 Dry Type Power Transformer Model

The varying current flow through the primary winding generates a varying magnetic flux in the core of the transformer. This varying magnetic flux generates a voltage on the secondary winding through induction. This is the principle of power transformers.

Oil-immersed power transformers have similar construction. There is oil filled in the tank. The principle above suits these two types of transformers as well. For these two transformers, the core and windings are placed in a tank and the tank is filled with oil or other liquid. The oil or other liquid filled in the tank transfers the heat generated by the windings and plays the role of insulation medium.

Figure 2.1-2 Oil Immersed Power Transformer

Figure 2.1-2 shows an oil-immersed three phase power transformer. From the cut-away tank, we can clearly see the core and windings inside. There are also some accessories such as bushings, on loading tap changer (OLTC), and wires.

2.2 Asset Management of Power Transformers

Industry is facing two significant challenges with their current transformer population. One is the aging, and the other is the continuous growth of the load (and/ or utilization) on each transformer. According to the International Energy Outlook 2010, the global power consumption grows at a rate of about 1.3 percent per year from 1990 to 2007. The growth in demand for electricity continues to grow in total energy use in the following 25 years (US Department of Energy, 2010).

In worldwide, most of the power transformers were installed after the Second World War. The average age of power transformers distributed in Australia and New Zealand in 2005 was 36 years (Enright & Lawrence, 2009). Usually the expected life for a power transformer is 35-40 years. This means these power transformers are reaching or exceeding their design life. As power transformers age, their mechanical and dielectric conditions degrade and the risks of failures increase. Thus, the aging problem of power transformers is quite a crucial question to the utility asset managers.

We note that in a 1975 study, the average age at the time of failure was 9.4 years. In a 1985 study, it was 11.4 years and by the 1997 study, the average age was 14.9 years (Bartley, 2011).

For those power transformers that have not reach their design life, through their service life, the levels of dielectric, thermal, chemical, and mechanical stresses on power transformers are different. Any of these conditions could weaken the performance of power transformers and generate risks of transformer failures (Steed, 1997).

Transformer failures cause catastrophic consequences including forced outage of the electrical system, loss of revenue, explosion and even loss of lives. On Nov 7th 2010, a power transformer exploded and started a fire near a nuclear power plant in New York, USA. It caused an emergency shutdown of one of the reactors. Due to the subsequent explosion, the fire lasted for over six hours. Another severe transformer explosion in western US, which occurred underground in 2008, destroyed one transformer and damaged one nearby. This event resulted in a four-month total power plant shutdown and a ten-month utility unavailability.

These two events show us how serious transformer failures can be and how important power transformers are in an energy system. Therefore, to detect the faults before power transformers fail and reduce the risk of failures are essential issues. Management of power transformer, taking into account the operation of the transformer over its life cycle particularly those nearing the end of life, presents a number of challenges to asset managers.

Traditionally, asset management strategies for power transformers refer to time based maintenance (also called preventive maintenance) and condition based maintenance (CBM). Condition monitoring monitors the initial running stage of an equipment and record specific parameter values over time. These values or conditions are then compared and the trend and the condition of the equipment or plant is estimated (Steed, 1997).

The main transformer condition monitoring diagnostic and detection methods include, but are not limited to, technologies such as:

(1) Oil Testing and Dissolved Gas Analysis (DGA): This detects transformer faults by analysing the composition of the gases liberated by insulation oil. This method can distinguish faults as partial discharge, overheating, arcing and degradation of insulation. It is used to detect faults like overheating of core and windings, electrical discharge, partial discharge and ingress of moisture/ water.

(2) Partial Discharge (PD) Testing: The two commonly used PD methods are detection of the acoustic signals and measurement of the electrical signals produced by the PD.

(3) Recovery Voltage Measurement (RVM): Detects the change in conditions of oilpaper insulation and water content of the insulation. It is used to detect the ingress of moisture/water and the insulating paper ageing.

(4) Frequency Response Analysis (FRA): Detects the deformation or damage of windings. People could get the internal state of power transformers by FRA technique. It measures the frequency response of power transformers.

(5) Temperature Measurement: Identify tap changer failures and overheating failures.

Among these diagnostic methods, DGA is the most widely used and reliable method to investigate transformer faults (Wang, Vandermaar and Srivastava, 2002). However, it cannot identify the exact location of faults and cannot indicate faults immediately.

Most of the above techniques support detection of power transformer failure. However, they are not always able to indicate the precise reasons that induce the failures.

Another issue in asset management of transformers is the absence of widely used, reliable models to estimate the remaining useful life. Reliable models will help making decisions of replacement time of power transformers. Some models do exist and they are described as follows.

Expert systems have been proved popular. An expert system is software based on human expertise knowledge. It helps solving problems in real world and as supplement information system. In asset management of power transformers, a scoring expert system is used to get an overall failure time expectation by combing assessment results of different failure indicators (Gao, McCalley and Meeker, 2009). The accuracy of an expert knowledge highly depends on the database it has. This health expert system contains three types of data: design/ manufacturing data, operational history and condition information. The process of health assessment use the expert system has four steps: (1) categorizing data; (2) statistical analysis; (3) scoring update; and (4) deciding what actions to be taken. Most diagnostic methods are related to single aspect of transformer condition. Expert systems can combine different diagnostic results and obtains an overall health index of power transformers. They help to predict faults of transformers and support decisions of what actions to taken under certain circumstances.

There have been a few studies to develop transformer life expectancy curves. One, a reliability centred maintenance (RCM) model based on experience of maintenance crew and historic data of the last 25 years failure occurrences of a power transmission company provides plenty of possible failure events and repair actions (Anders, 2006). In this study, transformer life expectancy curves are from asset age, failure data, and specific asset knowledge. Failure probability graphs for the transformers are obtained from these life expectancy curves.

A study of proportional hazard model of distribution transformer gives a graphical method to plot the failure behaviour with time. This is used to evaluate the effect of covariates on the failure performance and their failure rate (Prasad & Rao, 2003). The failure behaviour in this study is represented as the mean cumulative repair function (MCRF) developed by Nelson.

There are many factors acting in a complex way contributing transformer failures (Arshad, Islam and Khalip, 2004). Some researchers assert that a robust diagnostic method is more appropriate rather than exact one. Fuzzy logic model is one of these methods. In a study of power transformer asset management, a novel fuzzy logic technique with moisture and furanic compound as input variables, predicts the transformer remnant life and aging rate (Arshad & Islam, 2006). This model deals with the failures due to insulation deterioration and accommodates a number of random variables in the deterioration model.

In summary, a number of different approaches have been developed but they all make specific assumptions about the deterioration profile of the failure mode once detection has been made. There has been limited work, backed by test work, to understand how environmental factors influence deterioration profiles.

The inherent safety aspects of working also hamper work with transformers. Researchers are often limited to having to observe 'failures' in the field, by their nature these are unwanted and often unexpected. This limits the number of failures that can be used in model validation. The creation of failures, even on a laboratory scale, requires special care and safety considerations. These are described in Chapter 3.

2.3 Failure Modes and Effect Analysis

In industry, Failure Mode and Effects Analysis (FMEA) is a qualitative technique to identify potential failures of a system, process or machinery. It evaluates the likelihood and consequence of the failures and decides what actions to be taken (AS IEC 60812-2008). In this project, FMEA is a discipline technique to identify the potential failure modes of power transformers.

According to Australian Standard AS IEC 60812-2008, the steps of FMEA analysis are:

(1) Decide whether FMEA is required. The first step is to identify the function of FMEA in a project. Continue when it is necessary.

(2) Define system boundaries for analysis. The boundaries form the physical and functional interfaces between the system and its environment. Defining the boundaries helps to exclude the components or system outside the chosen system.

(3) Understand system requirements and function. This step requires FMEA users to identify the function of the chosen system and each part or subsystem and their functions in the chosen system.

(4) Define failure/ success criteria. It refers to the definition of failure. Based on the function of a system, when it fails to perform its function, it has a failure.

(5) Determine each item's failure modes and their failure effects and record these. The definition of failure mode is in what way a system fails. Different failure modes cause different effects. Identifying and recording them is the content of this step.

(6) Summarize each failure effect and causes. This step generates the summary of failure modes, causes and effects of a system.

(7) Report findings. Record all the findings in a FMEA worksheet recommended.

The aim of using FMEA in this project is identify the most significant and dominant failure modes in a power transformer and then find the causes of these failure modes. Only the first three steps in the FMEA process above are needed in this thesis. The FMEA is developed from published documents and industry sources. The FMEA of power transformers presented here is a compilation of these documents

Most of the large power transformers in use are oil-immersed transformers. Thus, this FMEA is based on literature about oil-immersed power transformers. An oil- immersed power transformer is mainly consisted of core, windings, tank, insulation oil, and other accessories. From Table 2.3-1 and Table 2.3-2, we can see that an oil-immersed power transformer can be divided into seven parts: core, windings, oil, insulation paper, OLTC, flying lead and casing pipe, and tank and appearance. The functions of each item are listed in the tables. The tables also list the failure modes, effects and current controls of each item. The value of this summary is to identify the main failure modes experienced by industry and make a pragmatic selection of the failure mode this project would investigate.

Table 2.3-1 FMEA Sheet (A) Done by This Project

Power Transformer FMEA Sheet (A)					
Item description and function	**Failure mode**	**Possible failure causes**	**Local effects**	**Final effects**	**Detection method**
Core: To provide a flux path as the magnetic part of the transformer	Partial overheating Suspension discharge	Heat dissipation failure Partial short circuit Multi-position earthing magnetic saturation Earthing fail Earthing wire damage	Shorten PT service expectancy;	Possible damage of core by fire; Discharge;	Oil testing: Dissolved Gas Analysis Infrared emission test; Frequency Response Analysis; Dissolved Gas Analysis; Electrical method;
Windings: To convert and transfer current, voltage and power	Overheating Winding deformation Inter-turn short-circuit Puncture	Aging Oil path blockage Short-circuit overloading Clamping force looseness; External short circuit; Insulation aging Over voltage Manufacture failure Winding vibration	Shorten PT service expectancy; Insulation damage, degradation;	Fire; Explosion; Partial discharge	Measure by sensors; Frequency Response Analysis; Dissolved Gas Analysis; Temperature monitoring; Partial Discharge testing;
Oil: To cool for windings and core; working as insulation fluid	Puncture Oil flow electrification Oil decomposition Overheating	Contamination Water Aging Over loading Discharge	Dielectric strength reduced; Affect heat transfer; Generate gases; Blocking oil path;	Fire; Discharge	Oil Testing (Furan & DP;) Recovery Voltage Measurement ; Moisture monitoring; Color checking; Dissolved Gas Analysis

Table 2.3-2 FMEA Sheet (B) Done by This Project

Power Transformer FMEA Sheet (B)					
Item description and function	**Failure mode**	**Possible failure causes**	**Local effects**	**Final effects**	**Detection method**
Paper: work as solid insulation	Insulation deterioration;	Water; DP (Degree of Polymerization);	Generate gases;	Aging rate increasing; Dielectric resistance degradation;	Moisture monitoring; Dissolved Gas Analysis (CO); Furan content (CO,CO_2) Frequency Response Analysis;
OLTC: To alter a transformer's voltage and current.	Overheating; Selector and diverter switches faults; Insulation get wet;	Contact wear; Contact coking; Mechanical wear; Aging Explosion in the atmosphere	Forced outage;	Fire ; Other components damaged;	Oil testing; Temperature monitoring; The operator being advised to manually initiate tap changers;
Flying lead &Casing Pipe: external insulation, connection to external components	Flashover Wire Breakage Overheating Suspension discharge	Insulation wet Partial copper exposure Welding failure Short circuit Welding failure Overloading Insulation wet Improper Construction Abnormal voltage	Insulation damaged,	Fire, explosion	PD (Partial Discharge) testing; Temperature distribution monitoring; Dissolved Gas Analysis;
Tank& Accessories Tank: To provide a space for the cooling oil.	Oil leakage; Terminal Connection loosen; Painting falling;	Manufacture faults; Installation faults; Tank Overpressure; Aging; Poor operating environment;	Degradation the insulation and heat transfer.		Regular appearance check;

2.4 Condition Monitoring on the Core and Windings of Power Transformers

A survey conducted by CIGRE in 1983 reveals the distribution of component failures of power transformers on each component. The results can be presented in the form of Figure 2.4-1.

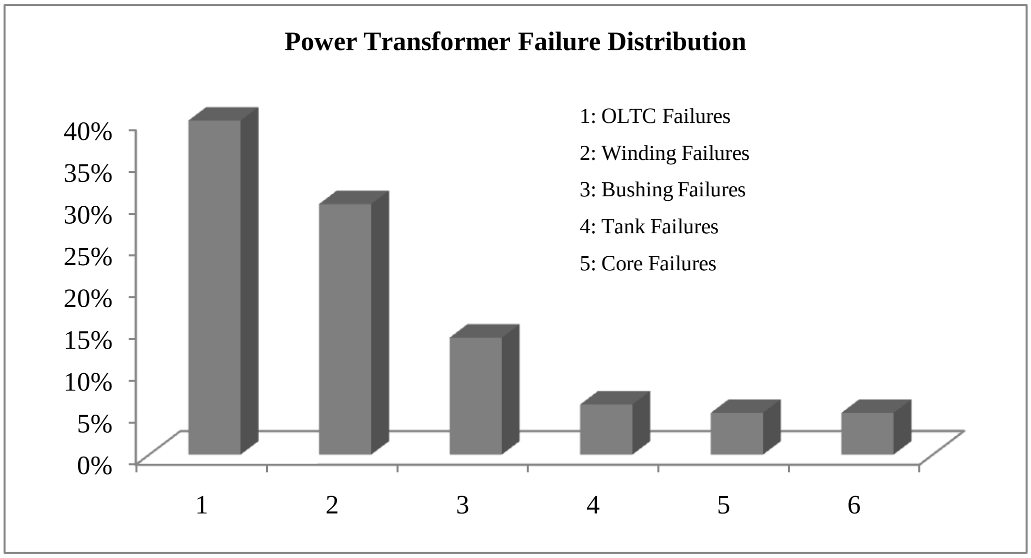


Figure 2.4-1 Power Transformer Failure Distribution

From Figure 2.4-1, we find that among all failures, the On-load tap changer (OLTC) failures are dominant (40%). The next high percentage failure is winding failures (30%). The percentages of bushing and tank failures are 14% and 6% respectively. Core failures occupy 5% of all transformer failures (CIGRE, 1983).

Different size range power transformers have different dominant failure modes. Ageing related problems are the dominant failure mode in smaller power transformers (<100MVA). Tap-changer failures constitute the highest failure rate in medium power transformers (100-400MVA). For large transformers (>400MVA), insulation failures are the main failures (Minhas, Reynders & Klerk, 1999).

According to IEEE standard 493-2007, a survey in 1979 revealed that winding failures occupy more than 50% of power transformer failures. These failures were initiated by some type of insulation breakdown or transient overvoltage (29.3% and 16.4% respectively). The next high percentage of failures was initiated by mechanical breaking, cracking, loosening, abrading, or deforming of static or structure parts. This reveals three highly possible causes of transformer failures: insulation breakdown, overloading, and structure deformation or loosening.

This information combined with guidance from industry contacts encouraged a focus on winding failures for this project, with a supplementary focus on core failures.

2.4.1 Failure Modes of Core and Windings of Power Transformer

The FMEA worksheet shows that the main failure modes of windings are overheating, deformation, short circuit and puncture. It also shows that the failure modes of core are overheating, discharge and suspension. In industry, condition monitoring is used to detect these failure modes as follows.

2.4.2 Condition Monitoring of Core and Windings of Power Transformer

As mentioned before, condition monitoring systems for power transformers include Dissolved Gas Analysis (DGA), Partial Discharge (PD), online gas monitoring, Frequency Response Analysis (FRA) for winding movement and deformation detection, Furfural Concentration Measurement, etc. For core and windings, condition-monitoring methods are Frequency Response Analysis Measurement (FRA) and vibration measurement. FRA is an effective method to detect the deformation of power transformer windings. Frequency response is the measure of any system's output spectrum in response to an input signal (Luther &Inglis, 1999). The change of physical parameters of power transformer affects the frequency response. These physical parameters are inductance and capacitance of transformer. Changes of inductance or capacitance may indicate a shifting or a generation of a new resonant pole frequency (Islam, 2000).

Change of inductance refers to disc deformation, local breakdown and winding short circuit. Change of capacitance reveals disc movements, buckling due to large mechanical stress, moisture ingress and loss of clamping forces (Jin, Zhu& Zhu, 2001). FRA is to identify the winding movements by identifying the physical parameters of windings from its frequency response.

The vibration of power transformers is a combined excitation in the core and winding vibration. Core vibration is generated by the excitation of magnetostriction and excitation of air gaps. The electromagnetic force generates winding vibration. In an oil-immersed power transformer, the vibration transfers from the oil to the tank. Therefore, the vibration can be measured at the tank.

The core vibration changes when the core clamping forces change. The movement of windings makes winding clamping forces change, and furthermore results in intensified vibration.

In a study of transformer diagnostic approach using FRA method (Gonzalez, Pleite & Salas, 2006), Gonzalez, et al measured the frequency response of a healthy transformer and faulty one respectively. By comparing the two results, they are able to identify the transformer failures. This study also developed new diagnostic method to identify which part of the transformer failed. The diagnosis method is to link the internal parts of the transformer with its frequency response and obtain their relationship. This study builds the frequency response model and figures out that core effect of frequency response locate at low frequencies while the winding effects locate at high frequencies. Using this model, the parameters of the cells defined in this study (Resistance R, Inductance L and Capacitance C) are calculated. The different cells represent the different components of transformer. By comparing the three parameters, it is possible to establish which part of the transformer fails. This study also develops experiments in laboratory. The experiment uses a handmade transformer assembled with a U shape ferromagnetic core and a copper winding and an impedance analyser of which the frequency sweep is from 100Hz to 4MHz. Following the comparison and modelling steps, the experimental results validate the preliminary conclusions and show that it is possible to establish the component with fault using frequency response analysis.

In the field, tank vibration monitoring is widely used to detect the winding deformation or movements. A study of vibration model used to monitor not only new but also in service transformer has successfully been done and achieved this goal (Garcia, Burgos &Alonso, 2005). This study analyses the vibration of the transformer and determine the locations on the tank to measure the vibration according to the analysis. It then determines the model input variables from the experimental results of variables that influence transformer vibration. It locates external sensors on the tank of the transformer and measures the vibration on the tank. The experimental results include the core vibration (no-loaded transformer), winding vibration and tank vibration from bottom. It eventually builds a tank vibration model, which includes variables of voltage, current, and temperature on the top of the oil.

A vibration measurement locates the sensors on the tank of the transformer and takes measurements twice in no-load condition. In no-load mode, the vibration is the vibration of core. It is because the electrodynamic force at windings is approximately zero at no-load mode of the secondary terminals (Ji, Shan & Li, 2000). Taking the measurement under loaded condition and subtracting the no-load results gets the vibration of windings. The authors asserted that the vibration of core is independent to secondary loading.

The vibration measurement and FRA measurement of power transformers can indicate the transformer faults instantaneously, reduce maintenance costs, decrease the risks of failures, and limit the severity of damages. Although the two methods are widely used now, for the other failure modes identified in the FMEA, (overheating, short circuit) they are not able to detect these failures.

Based on the tests, the possible causes and failure effects are connected. Models of power transformer can be built. From these models, diagnostics and prognostics of power transformer failures will become more scientific and accurate.

2.4.3 Creation of Winding and Core Failure Modes in the Laboratory

Previously, some work has been done to assess safely the core and winding conditions of the transformer (ABB, 2004). There are some literature to assist in determining what transformers to use, how to create the failure, and how to safely manage the testing of the unit to destruction (US Department of Interior Bureau of Reclamation, 2000). This project is to develop new methods on detecting core and winding failures of transformers in lab, including the method based on the vibration measurement of core and windings.

Overheating, short circuit and core deformation are the three failure modes examined in this thesis. When the transformer is overloaded, the current through windings increases and results in the winding temperature increase. With the cumulative effect of time, the heat generates faster in the windings than it is transferred to the environment. Overheating is generated in this case. When overheating occurs, there might be burning or melting consequences in the windings resulting in a short circuit.

In summary, this chapter has described the main failure modes experienced by power transformers in industry. It finds that windings are involved in a significant proportion of failures so this project will focus on windings. The next section describes the development of laboratory tests to safely create and observe winding failures.

Chapter 3 Description of Test Methods

There are two pieces of information required in failure diagnosis: what is supposed to happen and what actually happens. This section describes a series of tests designed to explore relationships (what actually happens) between input and output parameters of the test transformer under specific test conditions. The results of these tests are described in Chapter 4 and a comparison of the results obtained from physical modelling (what is supposed to happen) discussed in Section 5.

3.1 The Purpose of the Tests

The tests described in this section aim to

(1) Initiate specific core and winding failures in a safe and repeatable manner in the laboratory.

(2) Measure the change in performance parameters of healthy and damaged transformers under conditions associated with overheating, deformation and short circuit failures.

(3) Explore the influence of environmental factors on failure initiation and progression.

3.2 Tests of Power Transformers

In developing test procedures for this project, care was taken to understand current practices used in industry. Transformer tests are done for quality assurance and factory tests, condition assessment tests, diagnostic tests and safety tests. The quality assurance and factory tests are conducted during and after the manufacture of transformers to ensure the quality of power transformers. Tests to monitor the transformer running conditions and diagnose transformer failures are done by operators to ensure transformers operating safely and are maintain at appropriate intervals. These tests of power transformers are conducted based on the following Standards, which are widely used for transformer testing experiments.

(1) IEEE C57.12.00, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

(2) AS 60076.1—2005, Australian Standard Power transformers

These documents provide detailed, authoritative information of testing industrial power and distribution transformers. They are used by manufacturers and operators, provide minimum requirements for safe and reliable operation, and serve as valuable references of technical information (Harlow, 2007).

Some of the specific tests described in the Standards are for winding resistance, measurement of voltage ratio and check of phase displacement, measurement of short-circuit impedance and load loss, measurement of no-load loss and current, measurement of the harmonics of the no-load current, measurement of zero-sequence impedance(s) on three-phase transformers , tests on on-load tap-changers, operation test, auxiliary circuits insulation test.

During the literature review, this project did not identify any test procedures designed to deliberately fail transformers. This is understandable as transformer failure is a highly undesirable event with potential safety and fire implications. The absence of any written guidelines for deliberately failing transformers created a challenge for this project. As a result, how to design a procedure that allows a safe damage of transformers in a specific failure mode is a significant challenge for this project.

3.3 Test Design Process

The tests are to replicate these three failure modes in laboratory and observe related consequences. The test design process is presented in Figure 3.3-1.

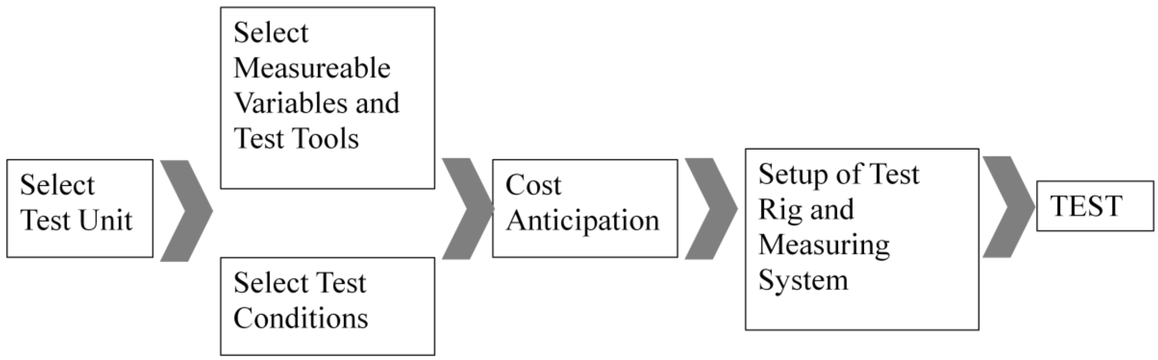


Figure 3.3-1 Test Design Process Map

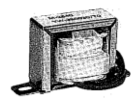
Each step is discussed in the following details.

3.3.1 Selection of the Test Transformer

A significant challenge in this project was the selection of a suitable test transformer. In laboratory, we are limited to the input voltages. The voltage we can use is 240V from the mains.

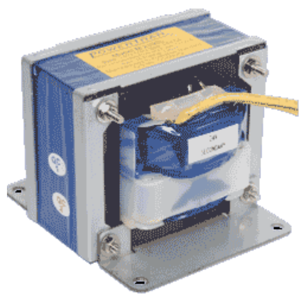
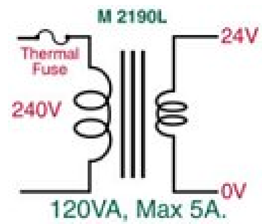
Table 3.3-1 shows three basic types of power transformers available in the local market and their specifications.

Table 3.3-1 Criteria for Test Transformer Selection

Alternatives / Criteria	Desired Criteria	**A** M2840 	**B** M6672L 	**C** M2190 
Input Voltage	240V	240V	240V	240V
Output Voltage	Below 36 V-	9V	0-24V	0-24V
Maximum Current	-	150mA	5A	5A
Rec. AC Fuse	yes	internal	500mA (external)	500mA (external)
Size	Be able to be fitted in the lab	31(H)×37(W)×32 (D) (mm)	60(H)×40(W)×70 (D) (mm)	76(H)×90 (W)×100(D) (mm)
Cost	low	$6.99	$16.50	$39
Availability	Local	DickSmith	Altronics	Altronics

Considering the output voltage range, size of transformer, and availability, all the three transformers satisfy the basic requirements. Due to the failure mode of core deformation, the test transformer must be able to be taken apart and reassembled. Therefore, transformer C is the best choice. The detailed information of this type of power transformer is listed in Table 3.2-2.

Table 3.3-2 Information of Test Transformer (M2190)

Outlook of the transformer	**Equivalent electric circuit map**	**Specifications**
		Primary Voltage: 240V AC Total VA Rating: 120VA Insulation: Class E (120 ÞC) Magnetising Current: <85mA Temperature Rise: <65°C Regulation: 10% Rec. AC Fuse: 500mA Weight: 2.19kg

The input voltage and output voltage of transformer M2190 are 240 V and 0-24 V respectively. The maximum current of this transformer is 5A. The transformer can be taken apart with a screwdriver allowing access to the windings and core.

The equivalent circuit diagram is shown in Figure 3.3-2. The diagram shows the winding resistances R, and the reluctances due to the leakage fluxes X, as well as a current generator for the magnetizing current I_0.

The phasor diagram for the transformer at full load is shown in Figure 3.3-3. Assume that the primary is supplying a current I_2 at a terminal voltage V_2 with phase angle θ. These are the first two phasors drawn. Now, to V_2 we add I_2R_2 in phase with I_2, and I_2X_2 in quadrature to find the induced voltage E in the secondary. The voltage -E is induced in the primary. The flux φ is at right angles to E, as shown. The current I_0 is necessary to create the flux, and is drawn with its proper relation to φ. The current I_2 is reflected to the primary as $-I_2$, and added to I_0 to find the total primary current I_1. Now that we know I_1, we can add I_1R_1 and I_1X_1 to -E to find the primary terminal voltage, V_1. In this diagram, the magnetizing current, and the voltages due to leakage flux and winding resistance, are greatly magnified so their effects can easily be seen.

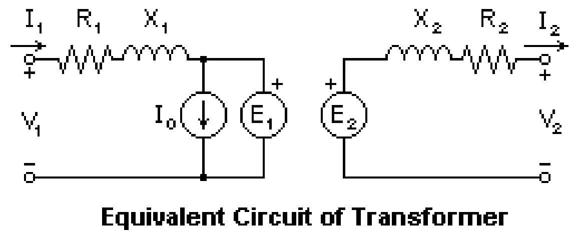


Figure 3.3-2 Equivalent Circuit of the Test Transformer

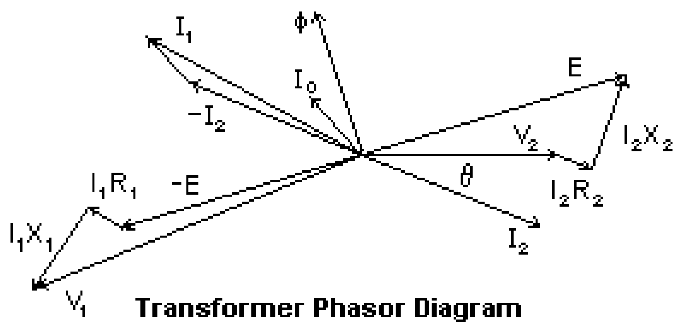


Figure 3.3-3 Phasor Diagram of the Test Transformer

In the process of exploring test transformer options, the author experimented with making small handmade transformers. The process to do this is described in Appendix 1. However, due to cost, time and quality control considerations the decision is made to proceed with the commercially available units.

3.3.2 Selection of Measuring Variables and Equipments

The variables and performance parameters for measurement are listed as follows:

Control Variables

(1) Input voltage,

(2) Environment temperature,

(3) Healthy and damaged core,

(4) Regular atmosphere and CO_2 atmosphere.

Performance parameters/observations

(1) Output voltage,

(2) Primary current,

(3) Secondary currents,

(4) Winding temperature,

(5) Vibration of the winding and core,

(6) Primary winding resistance,

(7) Secondary winding resistance,

(8) Visual inspection of damage,

(9) Smell of burning.

Table 3.3-3 lists the equipments and their specifications for measuring the control variables and performance parameters.

Table 3.3-3 Measuring Variables and Equipments

Variables	**Measuring Equipments**	**Usage& Specifications**
Input and Output Voltages		Agilent U 1252A Handheld Digital Multimeter: It is used to measure the input and output voltages. **Range** (true RMS AC value): 50.000mV-1000.0V; **Accuracy** ±(%of reading +No. of significant Digit): 1.5+60 (30Hz-45Hz); 0.4+25 (45Hz-10kHz);

Primary and Secondary Currents		Agilent U1252A Handheld Digital Multimeter with Agilent 34134 A AC/DC Current Probe: Simply crap the current probe on the wire you want to measure the current, obtain the current without break the circuit. **Range**: 10mA to 1.5A AC (1V/A range); 100mA to 60A AC (10mV/A range); **Accuracy**: ±2% reading ±5mA(1mV/mA) ±4% reading ±20 mA (500mA to 40A) **Operating Temperature:** 0 to 50°C
Temperature of windings		Infrared Thermometer: Make the thermometer point to the surface you want to measure, read the temperature of that place. **Range**: -30°C to 900°C **Accuracy** at 25°C ambient temperature: ±0.75% of reading **Ambient Operation Range**: 0°C -50°C **Response Time** (95%): 250mSec
Accelerometer of transformer	 	B&K PULSE Analyser with IMI ICP 608A11 vibration accelerometer: Put the accelerometer on the surface of the transformer core, and measure the vibration of the core. For the accelerometer, **Sensitivity**: $10.2mV/(m/s^2)$ ≈ 100mV/g **Measurement Range**: ±50 ≈ $\pm 490 m/s^2$ **Operation Temperature Range**: -54°C to 121°C **Frequency Range**: 0.5 to 10kHz

3.3.3 Safety Issues

Regarding to the safety requirements from the University of Western Australia, a risk assessment report is presented in Appendix 2 of this thesis.

The maximum test voltage in this project can be up to 270V (130% of the designed input voltage). Risks exist when experimenter contacts with live or damaged single insulated 270V electrical circuits. Besides, unexpected changes to the insulation integrity of the experimental circuits also induce these risks. There are also risks of fire or toxic fume as result of overheating.

Therefore, several safety management requirements are developed for these tests.

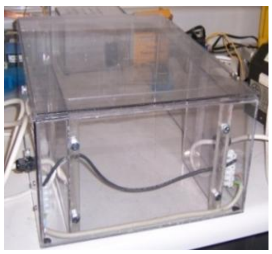
(1) Every step of the measurement process must have two layers of insulation to ensure isolation from hazardous voltages.

(2) Keep the flammable materials away from heat and ignition sources. Fit an automatic cut out switch to the primary circuit that will interrupt the supply voltage when current or temperature limits are exceeded.

(3) No work on this project should be carried out outside of normal working hours and researchers should not work alone.

According to these requirements, two safety boxes are made to use in the tests. Table 3.3-4 on the following page shows the outlook and functions of the boxes.

Table 3.3-4 Safety Boxes and Their Functions

Boxes	Functions
	1. This box is used to contain the transformer to avoid direct contact to the transformer. 2. The holes on the panels are for heat transfer.
	1. This box is used as the secondary insulation of the single wire measured the primary current. It connects the test transformer and the autotransformer 'Variac'. 2. Before measuring the current, put the current device inside and crap the wire. Then read the multimeter outside.

The two boxes are made of PVC materials; the thickness of the panel is 3-5mm. It is a non-conducting material and used as an insulation layer in this project. The researcher conducted all the tests when the supervisor was present.

3.3.4 Selection of Test Conditions/ Control Variables in This Project

In order to measure the change in performance parameters of healthy and damaged transformer under conditions associated with overheating, deformation and short circuit failures, it is necessary to create a "damaged" transformer. A transformer state (0) represents a healthy transformer while (1) represents the one with core "damaged".

To do this core damage by looseness is simulated removing a specific number of core plates. To explore the effect of temperatures at the test conditions, two test points were selected based on data from the Australian Bureau of Meteorology. In summer daytime temperatures range from 32°C to 40°C, while in winter, temperatures fall to 18°C to 23°C. Based on this, the tests temperatures are 20°C (0) and 40°C (1).

To observe the consequences of overloading test, the overloading test is conducted in air as regular atmosphere (0) and in CO_2 atmosphere (1) respectively. Table 3.3-5 shows the experimental design, describing the sets of tests planned for the transformers.

Table 3.3-5 Table of Test Control Variables

Test Condition Number	Temperature	Transformer States	Atmospheres	Input Voltage
1	0	0	0	0-270V
2	1	0	0	0-270V
3	0	0	1	0-240V
4	0	1	0	0-270V
5	1	1	0	0-270V

3.3.5 Test Plans

The failure modes defined in this project are overheating in windings, short circuit in primary winding and deformation of the core. To examine these failure modes, three types of tests (eight tests in total) are designed, including healthy transformer test, overload test and vibration test for a transformer with a loosened core. To identify the effect of ambient temperature on the transformer performance, the test transformer is operated under different temperatures: 20°C and 40°C. Therefore, there are three test steps.

Step 1: Test a healthy transformer when the ambient temperature is at 20°C and at 40°C respectively.

Step 2: Test an identical transformer under overloading conditions.

Step 3: Test a faulty transformer (with core looseness and winding looseness) at 20°C and at 40°C respectively.

The test conditions and the whole plan of eight tests in three test steps are shown in Table 3.3-6. The results of these tests are discussed in the following chapter.

Table 3.3-6 Test Conditions for the Three Steps of Tests

Test step	**Relationship explored**	**Transformer State**	**Ambient temperature**	**Core looseness**	**Input voltage**
1	Input voltage with Output voltages (Vi-Vo)	Healthy	20°C, 40°C	No	0-270V
2	Input voltage with Primary current (Vi—Ip); Output voltage and Secondary current (Vo-Is)		20°C, 40°C	No	0-270V
3	Input voltage with winding temperatures (Vi-Tp & Vi-Ts)		20°C, 40°C	No	0-270V
4	Input voltage with Primary current (Vi-Ip); Output voltage with secondary current(Vo-Is)	Healthy, Overloaded	20°C	No	0-270V
5	Winding temperatures with time (Tp & Ts with time)	Healthy, overloaded	20°C, 40°C	No	0-270V
6	Find out the relationship of overheating or short circuit failure modes with winding temperatures, currents	Healthy with shorted secondary windings	20°C	No	0-240V
7	Identify the role of Oxygen in test 6	As above test in CO_2 atmosphere	20°C	No	0-240V
8	Input voltage with vibration (Vi-vibration)	Healthy, core loosened	20°C	No	0-270V

Chapter 4 Experimental Results and Discussion

This chapter describes the execution of the tests designed in the previous chapter. It displays all the testing results followed by observations and discussions.

4.1 Tests of Input and Output Voltages of a Healthy Transformer

4.1.1 Hypotheses

This test has two hypotheses.

(1) The performance parameters (Input and output voltages) of a power transformer could be related to some transformer failures.

(2) The environmental factor (ambient temperature in this case) affects the input/ output of the primary and secondary voltages (Vi-Vo) relation.

4.1.2 Aim of the Test

This test aims to obtain the relationship between the input and output voltages. They are performance parameters of a healthy transformer. The relationship represents the transfer function of test transformers. The test also examine the effect of the ambient temperature change (20°C to 40°C) on the input and output voltage relationship.

4.1.3 Test Execution and Observations

This test use equipments including the digital multimeter, the safety boxes, an autotransformer that has an output voltage range from 0 to 270V, a regular thermometer which can display the ambient temperature, a heater and a radiator for increasing the ambient temperature, and some cables. In the test, we supply the transformer with different input voltages and measure the output voltages under different ambient temperature (20°C&40°C) respectively. The ambient temperature is normally around 20°C. The 40°C ambient temperature is obtained by using two heaters to heat the area around the test transformer. The following figure is the schematic diagram of this test.

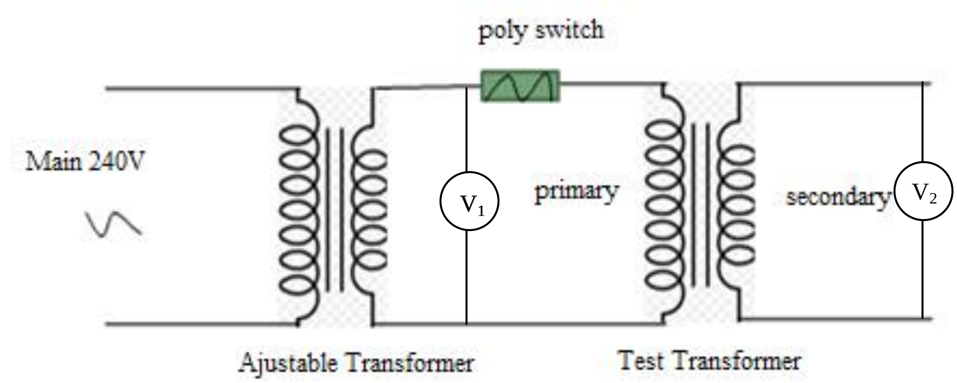


Figure 4.1-1 Schematic Diagram of Test 4.1

According to Figure 4.1-1, the test transformer obtains input voltage from the adjustable transformer. Voltage V_1 is the input voltage of the test transformer, while voltage V_2 is the output voltage of the test transformer. The heating instruments and the test rig are shown in the Figure 4.1-2.

(L) *(R)*

Figure 4.1-2 Heating System and Test Rig Setup

In Figure 4.1-2, the left plate (L) shows the heating system of the test. The test transformer is located in the middle of the two heaters. The heaters were turned on before the test. The test was started until the ambient temperature reached 40°C and then remaining steady. The right plate (R) shows the test setup when the ambient temperature is at 20°C. The autotransformer is connected to the mains. The range of the output voltage of the autotransformer is from 0V to 270V, this is used as the input voltage into the test transformer. The output voltage of the test transformer was measured when different input voltages are supplied to the test transformer. The results are shown in Figure 4.1-3

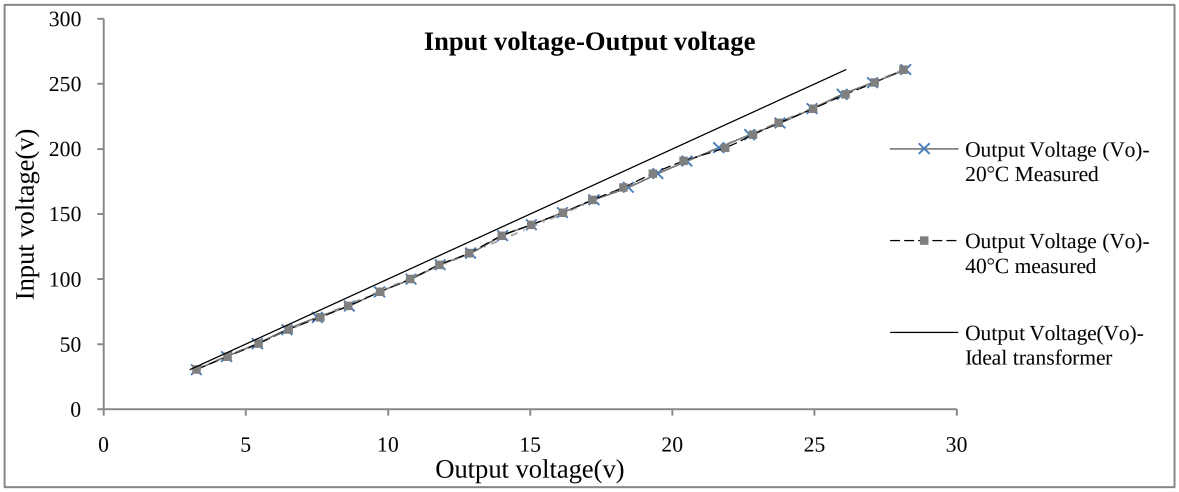


Figure 4.1-3 Output-Input Voltage Relationship Curve

Figure 4.1-3 shows the output voltage lines at different ambient temperatures. It also gives the output voltage line for the idea transformer. The solid line with marks on it represents the output voltage line when the ambient temperature is 20ºC while the dash one with marks represents that when the ambient temperature is 40ºC. The solid line with no marks is the output voltage in ideal circumstance calculated from the equation

$$V_i/V_o = 10/1 \qquad (4\text{-}1)$$

The ratio 10/1 is the number of turns of primary and secondary windings from the specification s of the test transformer.

4.1.4 Discussion of Test 4.1

From Figure 4.1-3, we observe that:

(1) The relationship between the input voltage (Vi) and output voltage (Vo) is linear.

(2) The Vi / Vo relation does not change much at different ambient temperature. In other words, the Vi / Vo is independent to the environmental temperature.

4.2 Test of Voltage and Windings Currents

4.2.1 Hypotheses

This test has two hypotheses.

(1) The performance parameters (primary (Ip) and secondary (Is) currents) of a power transformer could be related to some transformer failures.

(2) The change of environmental factor (ambient temperature in this case) affects the Vi-Ip and Vo-Is relation.

4.2.2 Aim of the Test

The aim of this test is to obtain the relationship of Vi-Ip and Vo-Is of a healthy transformer. It also validates the effects of the environmental factor (ambient temperature) on the two relations.

4.2.3 Execution and Observations

The test equipments in this test are the same with the test 4.1. The autotransformer supplies the test transformer with different input voltages. The primary and secondary currents are measured by the current probe and the digital multimeter. The following figure shows the schematic diagram of the test.

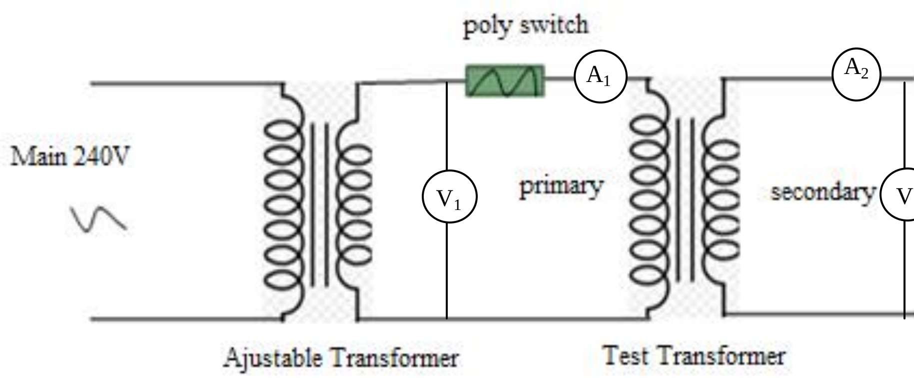


Figure 4.2-1 Schematic Diagram of Test 4.2

According to Figure 4.2-1, voltage V_1 is the input voltage of the test transformer, while voltage V_2 is the output voltage of the test transformer. Current A_1 is the primary current of the test transformer, while current A2 is the secondary current of the test transformer. The test results are shown in Figure 4.2-2 and Figure 4.2-3.

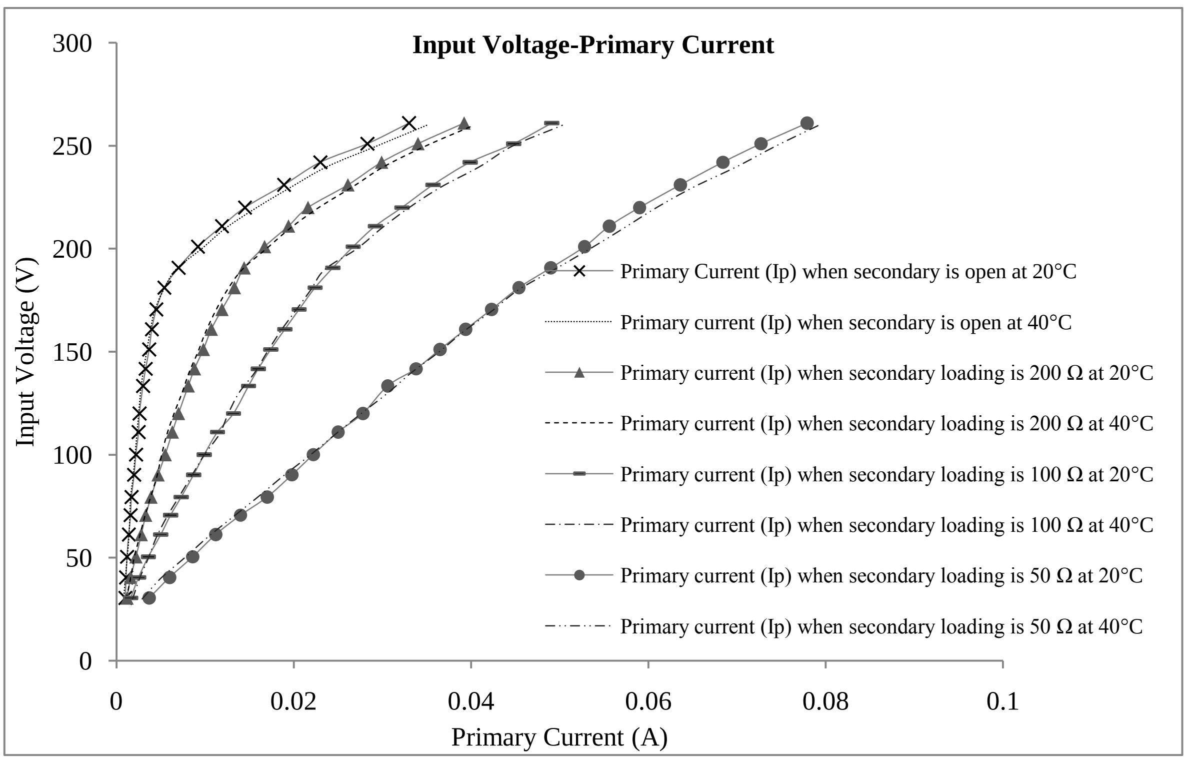


Figure 4.2-2 Input Voltage –Primary Current Curves

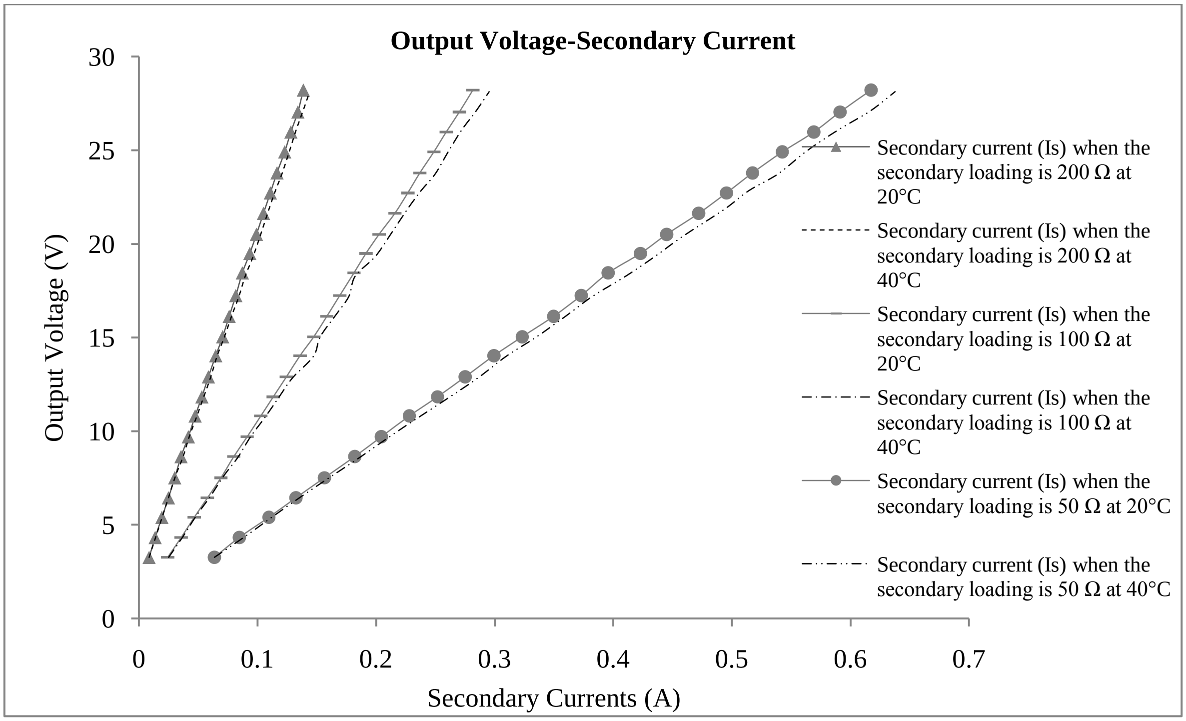


Figure 4.2-3 Output Voltage-Secondary Current Curves

Figure 4.2-2 shows the input voltage and primary current relationship. Figure 4.2-3 shows the output voltage and secondary current relationship. They are measured under different ambient temperature (20ºC and 40ºC) and different loading conditions.

From the results in Figure 4.2-2 and 4.2-3, we observe that:

(1) The primary current increases with the input voltage increases.

(2) When the loading is 50Ω, the relationship between primary current and input voltage is linear.

(3) The relationship between the secondary current and output voltage is linear.

(4) Both the primary and secondary current change very little at different ambient temperatures. In other words, the ambient temperature change does not affect the transformer currents.

(5)When the loading is small enough, the relation of primary current and input voltage is linear. It means the input impedance of the transformer is a constant.

(6)The results reveal that increasing temperature by 20°C is not sufficient to change the condition of winding insulation.

4.3 Test of Input voltage and Winding Temperatures (Vi-Tp, Ts)

4.3.1 Hypotheses

This test has two hypotheses.

(1) The performance parameters (primary and secondary currents) of a power transformer could be related to some transformer failures.

(2) The change of environmental factor (ambient temperature in this case) affects the Vi-Ip and Vo-Is relation.

4.3.2 Aims of the Test

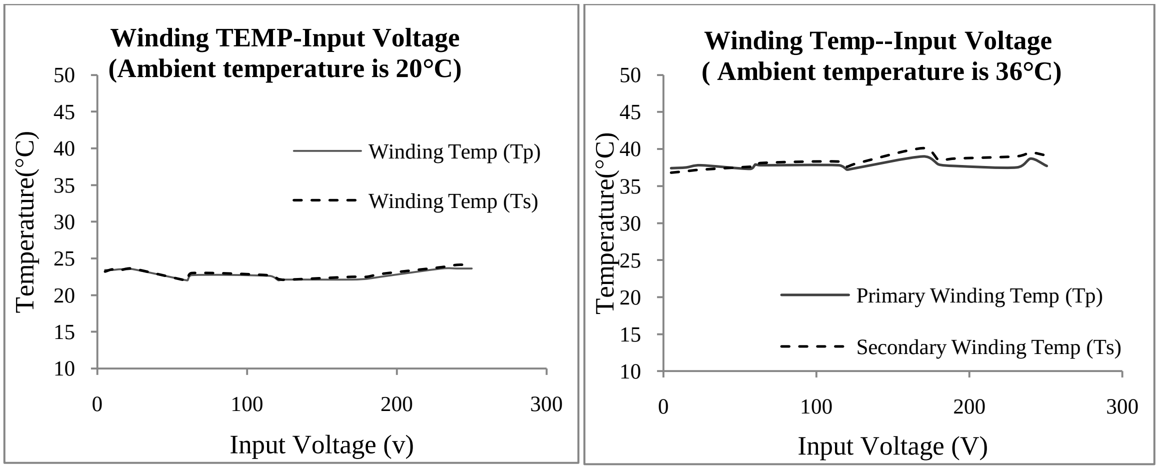
The aim of this test is to identify

(1) The relationship between voltage and winding temperatures

(2) The effect of the ambient temperature on this relationship.

4.3.3 Execution and Observations

The test equipments in this test include the equipments in test 4.1 and 4.2 and an infrared thermometer. In the test, the transformer is supplied with 0-240V AC input voltage. An infrared thermometer measures the temperatures of the surface of the primary and secondary windings. The secondary loading is 50Ω. The schematic diagram of this test is same with the test 4.1. The results of the winding temperature are shown in Figure 4.3.1.



(L) *(R)*

Figure 4.3-1 Primary and Secondary Windings Temperature-Input Voltage Curves

Figure 4.3-1 shows the winding temperature change with the input voltage changes. The left plate (L) shows that when the ambient temperature is 20ºC while the right one (R) shows that when the ambient temperature is around 36ºC. The test is designed to be performed under the ambient temperature of 40 ºC. However, the experimental condition in the lab can only maintain the ambient temperature at around 36 ºC in this experiment. The solid curves represent the temperature of primary windings while the dash ones represent the temperature of secondary windings.

From the test 4.3, we observe that:

(1) The winding temperature shows fluctuation around the environmental temperature.

(2) There is no linear increase relation between input voltage and winding temperatures.

The results reveal that the heat generated is not large enough to destroy the winding insulation. It also reveals that the 20°C temperature change does not affect the performance of transformers.

4.4 The Voltage with Current Test of a Healthy Transformer Overloaded

4.4.1 Hypotheses

There are two hypotheses in this test.

(1) Making a power transformer overloaded generates failure modes of overheating and short circuit.

(2) Time has effect on the winding temperature when a power transformer is overloaded.

4.4.2 Aims of the Test

The aims of this test are to identify

(1) The failure mode when it is overloaded,

(2) How much current is needed to destroy the transformer windings and what is the corresponding temperature,

(3) At certain current level, the temperature change of the windings as a function of time.

4.4.3 Methodology of the Test

The power rate is equal to the input voltage multiplies by the primary current or the output voltage multiplies by the secondary current. To overload the transformer, the input voltage should be large enough to make sure that the current is large. Then the power rate will exceed the specified value, which means the transformer is overloaded.

4.4.4 Execution and Observations

It measures the winding current change with ambient temperature change when the primary current exceeds 500mA. It also measures the windings temperature change with time when the transformer is overloaded.

In the previous tests, we find that the smaller the secondary resistance is, the larger both the primary and secondary current is. When connect a small resistance in the secondary circuit, it could generate a large secondary current. In this test, two HID bulbs connected in series are the secondary loading. The resistance at normal temperature is only 3Ω (25 ºC). Furthermore, the HID bulb changes its resistance when the current changes. It is a protection from short circuit.

Other equipments in this test are autotransformer, safety boxes, the digital multimeter, the current probe, the infrared thermometer, regular thermometer, and connecting cables.

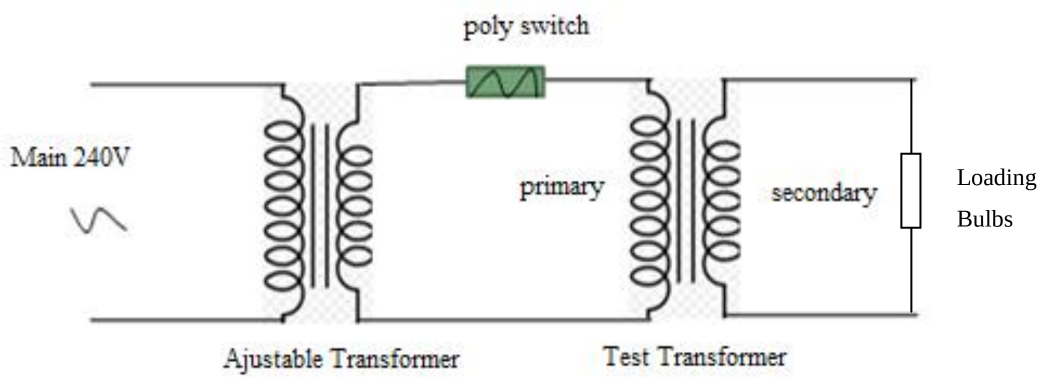


Figure 4.4-1 Schematic Diagram of the Test 4.4

Figure 4.4-1 shows the schematic diagram of the test 4.4.

(L) *(R)*

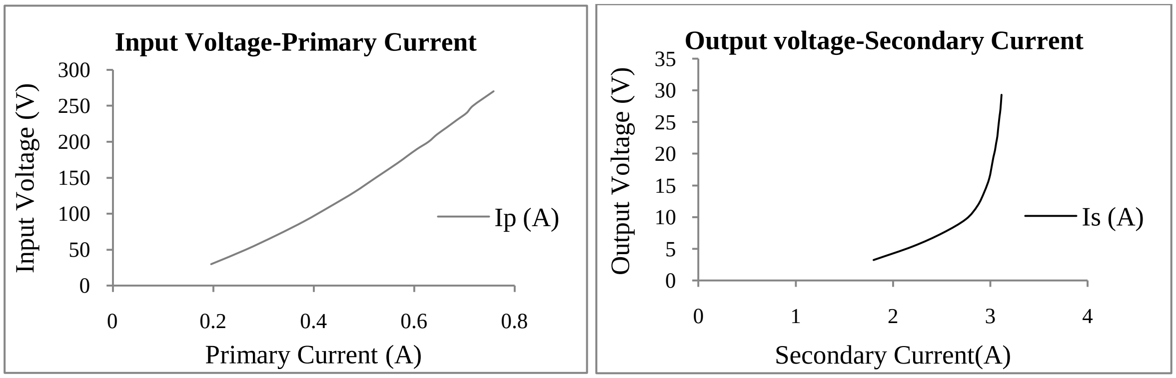
Figure 4.4-2 The Two HID Bulbs and the Heating System

Figure 4.4-2 shows the two HID bulbs (L) and the heating system (R). The heating system is made up of two heaters and a thermometer as the equipments used in previous tests.

Figure 4.4-3 Test Setup

The Figure 4.4-3 shows the test setup for the overloading test. The test setup is not much different from that in the previous tests.

Figure 4.4-4 shows two curves that represent the primary current change with input voltage and secondary current change with the output voltage respectively when the secondary loading is two HID bulbs. The dash curve is the primary current while the solid one is the secondary current.



(L) *(R)*

Figure 4.4-4 The Relationship of Voltages and Currents

We can observe that

(1) The primary current is almost linear, but the output current is not after the input voltage reaches 100V.

(2) The output V-I relation in nonlinear is because the HID bulb changed its resistance according to the current change. From Figure 4.4-4 (R), we find that the resistance increases when the output voltage is larger than 10V.

4.5 Test of Winding Temperature with Time (Tp,Ts-t)

4.5.1 Hypothesis

The hypothesis of this test is the winding temperature increase with time when the transformer is overloaded.

4.5.2 Aims of the Test

The aims of this test are to identify

(1) The failure mode when the transformer is overloaded,

(2) How much current is needed to destroy the transformer windings and what is the corresponding winding temperatures,

(3) The winding temperature as a function of time.

4.5.3 Test Observations

Figure 4.5-1 shows the schematic diagram of this test.

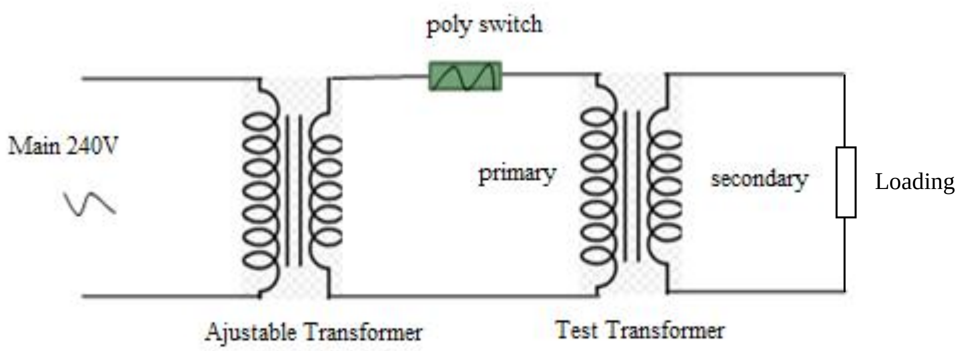
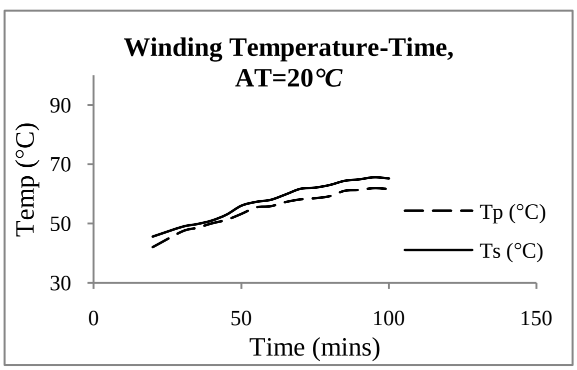
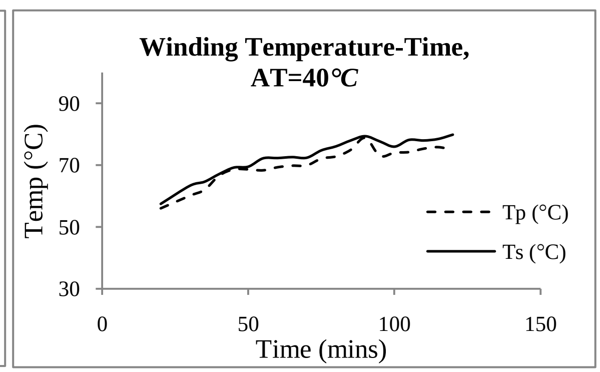


Figure 4.5-1 Schematic Diagram of the Test 4.5

Figure 4.5.2 shows the results of winding temperature change with time when the transformer is not overloaded (the input voltage Vi is equal to 187V, input current Ip is equal to 0.586A, and the output current Is equals to 3A). The VA rate is actually 110VA. The two figures show the results when the ambient temperature (AT) is at 20°C and at 40°C, respectively.





(L) *(R)*

Figure 4.5-2 Winding Temperature as a Function of Time

Figure 4.5-2 shows the change of winding temperature with time under different ambient temperatures (20°C and 40°C separately). At 20°C, in 110 minutes, the winding temperature reaches to 60-70°C. At the end of this period, the temperature keeps in stable level. At 40°C ambient temperature, the two temperatures exceed 80°C in 120 minutes. The transformer did not fail even when the winding temperature is more than 80°C.

Figure 4.5-3 shows the results of winding temperature change with time when the transformer is overloaded (the input voltage Vi equals to 238V, input current Ip equals to 0.690A, and output current (Is) is equal to 3A). In this case, the VA rate is 160VA.

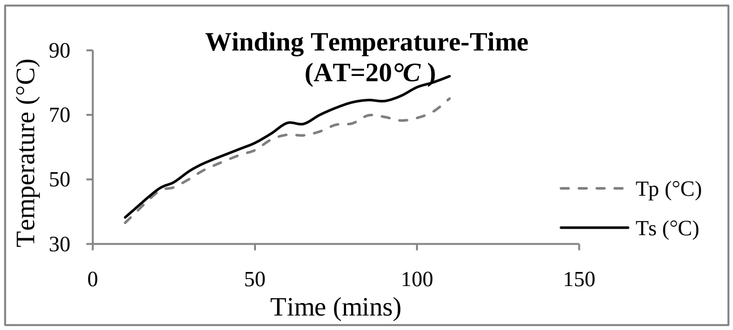
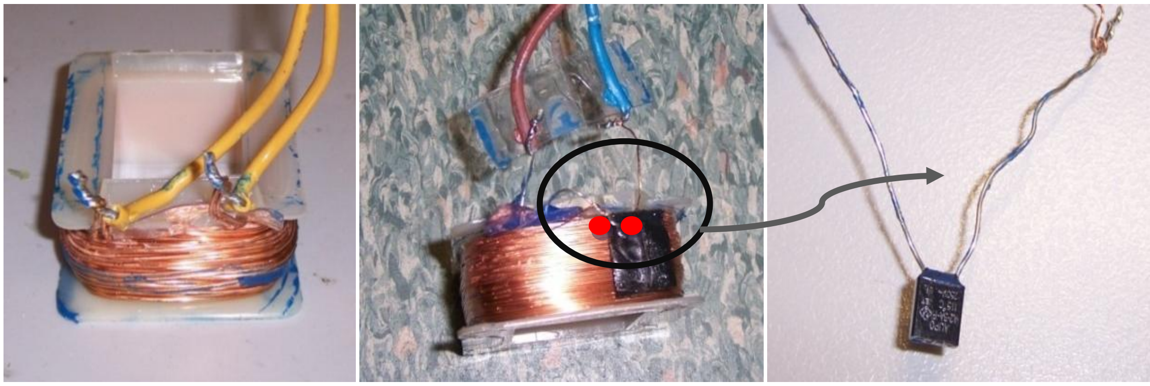


Figure 4.5-3 Winding Temperature as a Function of Time

Figure 4.5-3 shows the change of winding temperature with time (AT is 20°C). It shows that the winding temperature increases slowly with time. At the point of 110mins, the transformer stops working. The current drops to zero. At this time, the temperature of the windings surface is more than 80°C. During the test, there is no burning smell or smoke. To identify if there is any breaking of the winding wires due to overheating, the resistance of primary and secondary windings are measured after the experiment. The thesis used DC measurement for the resistances. The primary result shows infinite and it means the primary winding is broken. The secondary winding is the same value as it is before test. It indicates the secondary winding is not damaged.

Tearing down the transformer, we were able to view the secondary and primary windings in Figure 4.5-4.



(A) *(B)* *(C)*

Figure 4.5-4 The Secondary Winding, Primary Winding and Thermal Fuse inside the Primary Winding

Figure 4.5-4 shows the secondary winding (A), primary winding (B) and a thermal fuse used in the primary winding (C). The primary winding shows no defect. The thermal fuse works before the winding damaged to protect the power transformer. The maximum operating current of the fuse is 2-3 A; and the fuse operating temperature is 115 °C. The temperature we obtained in step one is the surface temperature. When the surface temperature is over 80 °C, the inside temperature is very likely to reach the fuse operating temperature 115 °C.

4.5.4 Discussions for Test 4.5

(1) Winding temperature increases slowly with time.

(2) Ambient temperature change (20°C-40°C) does not affect the winding temperature when the transformer is not overloaded.

(3) The thermal fuse installed in the transformer protects the transformer from destroying from overloading.

(4) The transformer turns ratio is 10:1. However, Is/Ip =3/0.586 in the first case and 3/0.69 in the 2nd case. This is induced by the transformer loss and experimental errors.

4.6 Overloading Test of a Healthy Transformer with Thermal Fuse Shorted

4.6.1 Hypothesis

The hypothesis of this test is that removing the protection of the thermal fuse, making a power transformer overloaded generates failure modes of overheating and short circuit.

4.6.2 Aims of the Test

The aims of this test are to

(1) Generate overheating and short circuit failure modes in laboratory,

(2) Identify how much current is needed to destroy the transformer windings and what is the corresponding the winding temperature.

4.6.3 Execution and Observations

The VA rate of the test transformer is specified as 120VA, while the maximum primary current is 500mA. The maximum input voltage the test transformer can get is 270V. Even if the input voltage is the maximum value, the current is still not large enough to kill the winding. However, shorting the secondary side gets a larger current.

From Tests 4.4 and 4.5, we know that the maximum primary current is nearly 1A when the 3ohms resistance is connected in the secondary side. At this current level, the transformer windings could not be damaged. In order to achieve test aims, the new tests require larger current. To short the secondary circuit is an easy way to get a larger current. The thermal fuse is used to protect the windings; it protects the windings when the temperature is too high. To effectively destroy the winding we first short circuit the fuse as shown in Figure 4.6-1. In this way, large short circuit current in the secondary winding will generate large heat to destroy the winding.

Figure 4.6-1 The Shorted Fuse

The two terminals of the fuse are connected by a copper wire. In this way, the fuse is shorted and does not work anymore.

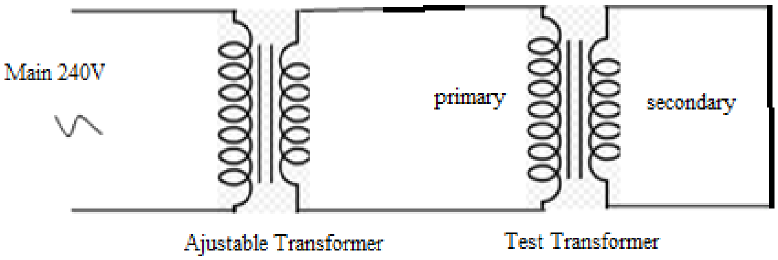


Figure 4.6-2 Schematic Diagram of the Test 4.6

Figure 4.6-2 shows the schematic diagram of test 4.6. The fuse is shorted and the secondary of test transformer is also shorted.

Figure 4.6-3 shows the setup rig in this test.

Figure 4.6-3 Test Setup

The input voltage is initially given by 30V, and then increases to around 210V very quickly (within one minute). The primary current is also raised to 2.4A. Then in about 5 seconds, there is smoke rising from the transformer and a smell of burning came from the transformer. Test stops.

Tearing down the transformer, we find the winding is damaged by the test. The following figure shows the damage to the winding former and materials around it.

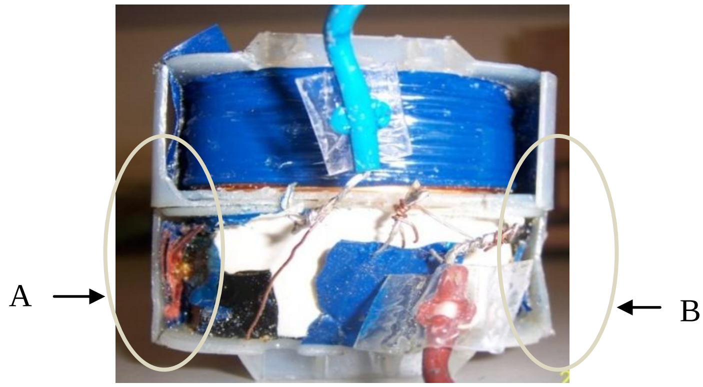
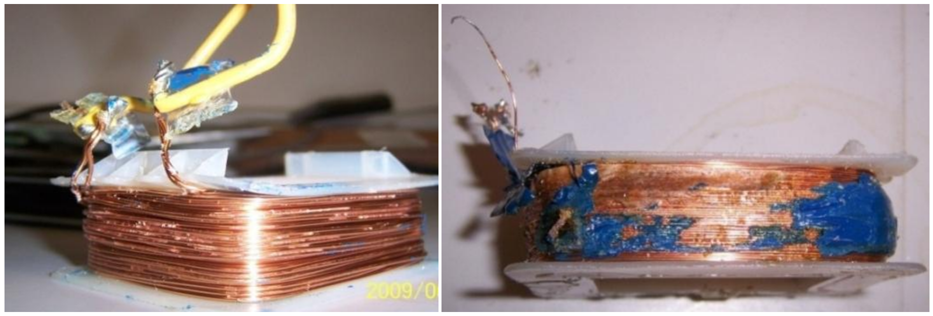


Figure 4.6-4 The Windings after the Overloading Test

Figure 4.6-4 shows the primary winding (lower) and the secondary winding (upper) after the overloading test. The plastic winding former has some deformation at location A and B. The glue there is also burned. This is because the larger current immediately generated huge energy and makes those materials burning. That is the reason why in the test, some smoke was released from the transformer.

Before the test, the resistance of the primary winding Rp is measured 19.95Ω; while that of the secondary winding Rs is 0.52Ω. After the test, Rp is 1.03Ω while Rs is 0.52Ω. The resistance of the secondary winding shows no change after the test which indicates that the secondary winding is not damaged by the test as shown in the picture below. The resistance of the primary winding becomes much smaller is due to the fact that the larger current makes some insulation melted and caused short circuit.



(L) *(R)*

Figure 4.6-5 Secondary Winding and Primary Winding after Overloading Test

Figure 4.6-5 shows the secondary and primary windings after the test. The left one (L) is the secondary winding. There is no visible damage on it. The right one (R) is the primary winding. We can see the glue on it is burned; the insulating varnish must also be burned. Then there might be some short circuit points on the winding. In this way, the resistance of the primary winding significantly decreases.

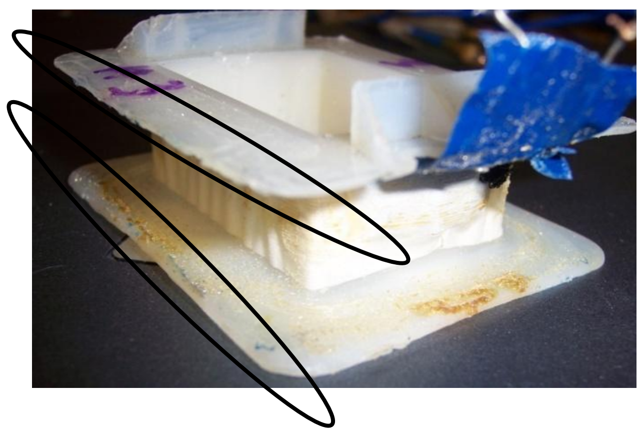


Figure 4.6-6 The Plastic Frame of Winding after Overloading Test

After taking off the primary winding, the frame of winding is shown in Figure 4.6-6. We find clear deformation by heat at the edge of it. The burning sign is clear. It means the hot spots of the winding might be on the outer turns of the wire in primary winding.

4.6.4 Discussion of Test 4.6:

(1) Overloading is replicated in the laboratory successfully.

(2) The overlading is described by the increase in the current and the winding temperature.

(3) It is short circuit failure.

(4) The test shows the outer turns has higher temperature as the result of the primary winding failure (insulation failure).

4.7 Overloading Test in Carbon Dioxide and Air

4.7.1 Hypothesis

The hypothesis of this test is that the existence of oxygen affects the overheating results. It is the reason why the outer turns burns before the inner turns.

4.7.2 Aims of the Test

The aims of this test are to

(1) Observe the consequences of the tests and see the effect of oxygen in the overloading test.

(2) Identify the effect of oxygen on the overheating failure mode.

4.7.3 Methodology of the Test

From the previous overloading tests, we know that the transformer generates a smell of burning and smoke when the primary current is around 2.4A. After we tear down the windings, we find that the burning spots appeared at the outer turns of the primary winding. However, the temperature of the inner turns of the winding should be higher than that of the outer turns because of the heat transfer. We suggest that the outer turns of the winding burns before the inner turns is due to the availability of oxygen which is an necessary condition for burning.

To verify this, two tests are executed. One of them uses a new transformer (labelled as No.5) to repeat the former test; the other uses another identical transformer (labelled as No. 6) in a carbon dioxide filled box. Most substances can burn in the oxygen but not in carbon dioxide. If the hypothesis is correct, the first test should have the same result with the previous test while there should not be any burning phenomenon in the second test.

4.7.4 Execution and Observations

The schematic diagram of this test is the same as that of test 4.6. Setup of the Tests is shown in the figure below. Put some dry ice in an empty box and wait for a while. The dry ice volatilizes and CO_2 fills the box. To check if the box is full of CO_2, light a match and slowly move it to the box, if the light is off, it means it meets carbon dioxide. Execute the experiment until the box is fully filled with CO_2.

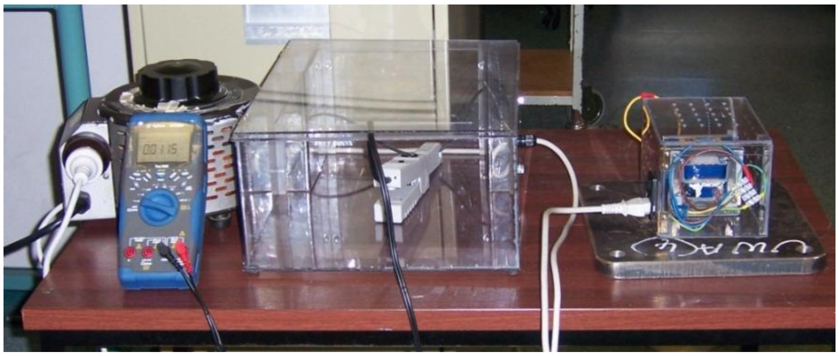


Figure 4.7-1 No.5 Transformer Test in Air

Figure 4.7-2 No. 6 Transformer Test in CO_2

The transformer labelled as No. 5 is settled as in Figure 4.7-1 while the transformer labelled as No. 6 is settled as in Figure 4.7-2. The thermal fuse is shorted. For No. 5 transformer, the input voltage increases from 30V to 165V, the primary current increases to 2.0A. Keep it for 10 seconds; there was a slight burning smell. Measuring the resistance of the primary and secondary windings, there is no difference from the value measured before the tests. This indicates no damage to the windings. The smell may come from those paper and plastic material.

Removing the paper and plastic materials, the transformer is shown in Figure 4.7-3. The test repeated. When the input voltage increases from 30V to 210V, the primary current was measured 3.5A. Keep it for 20 seconds. There was smoke and burning smell. The test stops.

(L) *(R)*

Figure 4.7-3 No.5 Test Transformer & No.6 Transformer

For the other one labelled as No.6 as shown in Figure 4.7-3, it is tested in CO_2 environment. The test transformer with a safety box is placed in the large plastic box filled with CO_2 (Figure 4.7-3 R). The cables connect the test transformer to the mains. The thermal fuse is also shorted. The input voltage increases from 30V to 210V and stayed for 30 seconds. When the input voltage was 210V, the primary current was measured around 3.5A. There is no burning smell or smoke. The test stops after the 30 seconds.

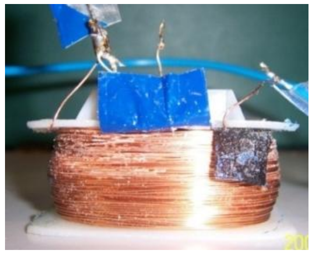
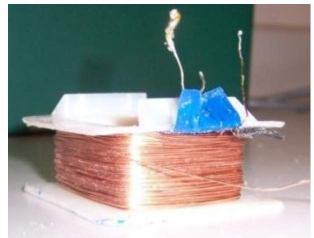
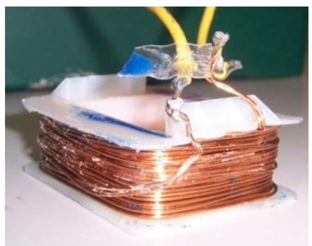
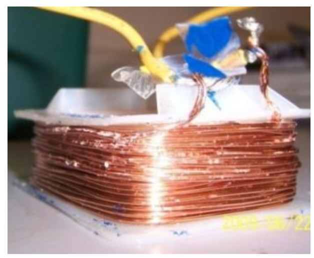
For the two transformers, the resistance of the primary and secondary windings before and after the tests are recorded in the following table 4.7-1.

Table 4.7-1 Resistance of the Windings

Transformer	**Test conditions**	**Before the test**		**After the test**		**Smoke or burning smell**	**Visible damage**
		Primary winding	Secondary winding	Primary winding	Secondary winding		
No.5	Test in air (1)	21Ω	0.74 Ω	20 Ω	0.68 Ω	Burning smell	No
	Test in air (2)	20 Ω	0.68 Ω	20 Ω	0.65 Ω	Burning smell and smoke	No
No.6	Test in CO_2	20.1 Ω	0.72 Ω	19.66 Ω	0.75 Ω	No	No

From the results above, we get that the resistance of the windings changes less than 10%. There is no visible damage to the windings. After tearing down the two transformers, the pictures of windings of the two transformers were shown in Table 4.7-2.

Table 4.7-2 Winding Damage after Overloading Test

Category	**No. 5 Transformer**	**No. 6 Transformer**	**Remark**
Primary winding			1. Both the two primary windings show no change on outlook. 2. The resistance values of the two primary windings do not change sufficient to say it is broken.
Secondary winding			No visible damage on both secondary windings can be found.
Primary winding former			No deformation or burning sign show on the former.

From the above pictures, we can see that there are no burning signs and no heat deformation on both transformers.

4.7.5 Discussion for Test 4.7

For the No.6 transformer tested in CO_2 atmosphere, even though the temperature of the windings could be very high, it could not burn, because of the existence of the carbon dioxide. For the No.5 transformer tested in air, there was smoke generated in the test. This could be due to the burning of the paper and plastic materials. After these materials are removed, the burning damage should be the varnish on the copper wire, but it is not visible.

The test did not result in winding short circuit; the resistance kept almost the same before and after the test.

The outer turns of primary windings burned instead of the inner turns, because of the existence of the oxygen. The insulation paper and plastic material burned in the test (1) on transformer No.5 because it is on the outside of the windings. The source of the smell in test (2) on transformer No.5 is not clearly identified. It could be due to the melting of the varnish, but there is no visible damage of the wire.

4.8 The Vibration Test

4.8.1 Hypotheses

There are two hypotheses in this test.

(1) The input voltage has effect on the vibration of the transformer;

(2) The looseness of the core will increase the vibration level of the test power transformer.

4.8.2 Aims of the Test

The aim of this test is to identify

(1) the vibration level of test transformers;

(2) the effect of input voltage change and core looseness on transformer vibration.

4.8.3 Background

Previous publications show that monitoring transformer vibration is a useful and reliable diagnosis and preventable method on the maintenance and management of power transformers. The vibration of a transformer is mainly generated by the windings and core. The looseness of the core may affect the vibration results.

4.8.4 Execution and Observations

In the test, a transformer with several pieces of core removed is used to replicate the core looseness situation. The vibration of a normal healthy transformer is measured for comparison. The vibration of transformer is measured at different input voltages. The transformer is earthed to reduce the electrical noise when the tests are executed. The accelerometer is located on the top of the core. Then the vibration results of the two transformers are compared.

The PLUSE analyser system and the ICP 608A11 accelerometer are used in this test. The test set up is shown in Figure 4.8-1.

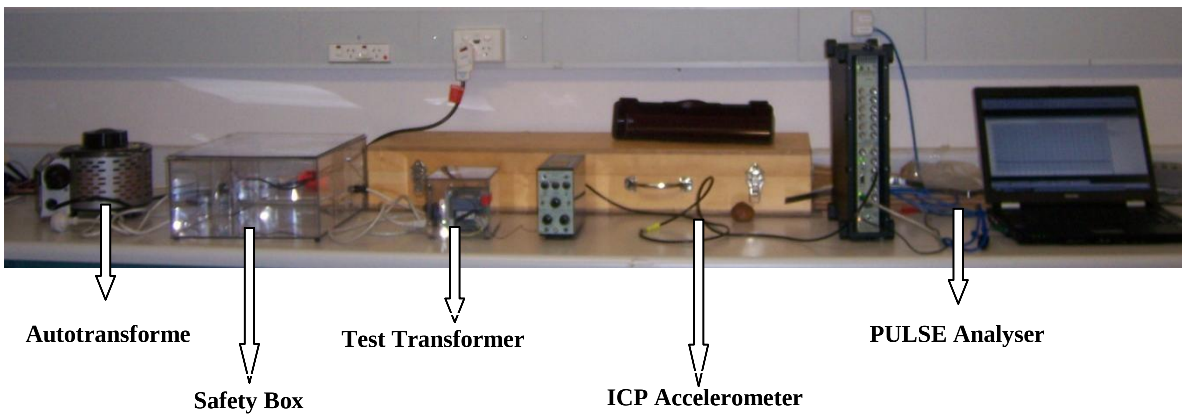


Figure 4.8-1 Vibration Test Setup

Figure 4.8-1 shows the components and setup of the test. Figure 4.8-2 shows the position of accelerometer on the test transformer.

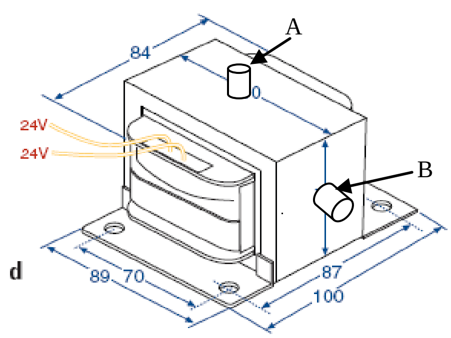


Figure 4.8-2 Schematic Diagram of Accelerometer Position on the Test Transformer

There are two positions to locate the accelerometer. One is on the top of the transformer core, as shown A. The other is on the side of the transformer core, as shown B. For the normal healthy transformer and the one with five pieces of core removed, the vibration results at different input voltage are shown below separately.

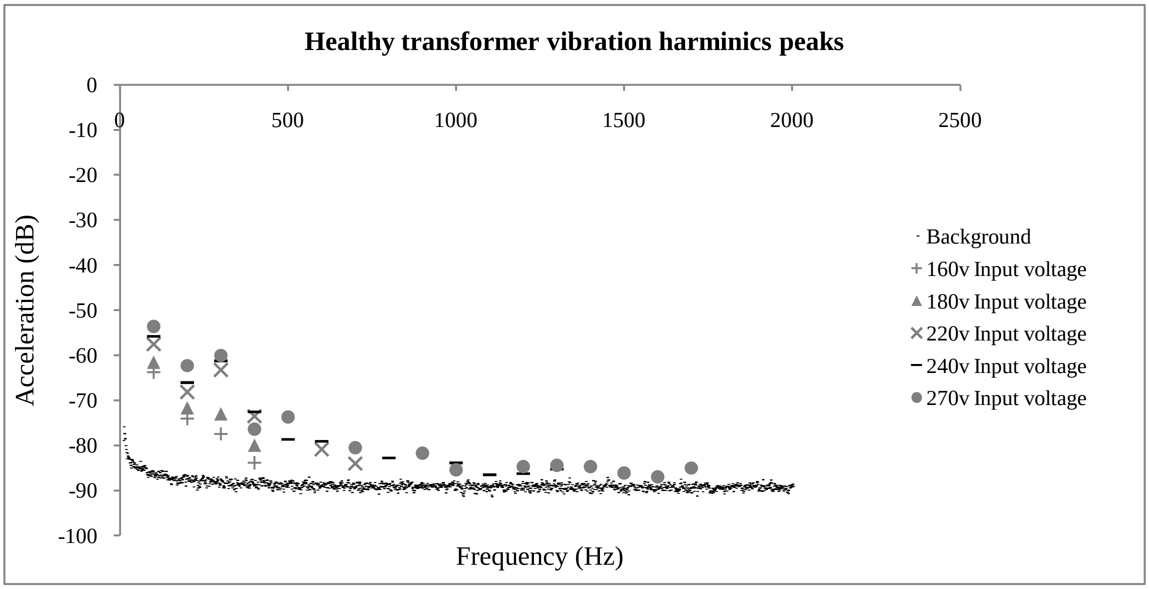


Figure 4.8-3 Healthy Transformer Vibration Harmonics Results

Figure 4.8-3 shows a summary of the vibration harmonics peaks of a healthy transformer at different input voltages. The secondary circuit is open.

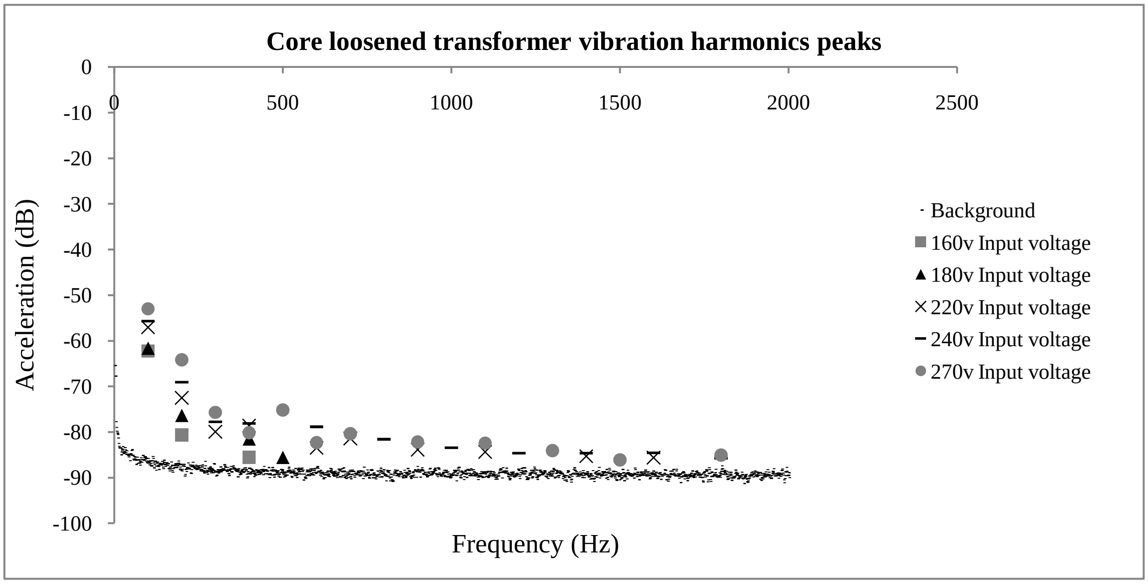


Figure 4.8-4 Harmonic Peaks of Transformer with Five Pieces of Core Removed Vibration

Figure 4.8-4 shows the summary of harmonics peaks of vibration results of the transformer with five pieces of core removed. The secondary circuit is open.

Observations from the two figures are:

(1) The biggest vibration harmonic peak appears at 100Hz;

(2) At low frequencies (100Hz, 200Hz, 300Hz, 400Hz), the larger the input voltage is, the larger the harmonic peak value is.

(3) High frequency harmonics (more than 800Hz) appear when the input voltage is 240Vand 270V for a healthy transformer core; While these appear when input voltage is 220V, 240v and 270 for a loosened transformer core.

(4) The changing trend of the harmonics at high frequencies is not clear.

Figure 4.8-5 compares the core vibration results of the two transformers at same input voltage.

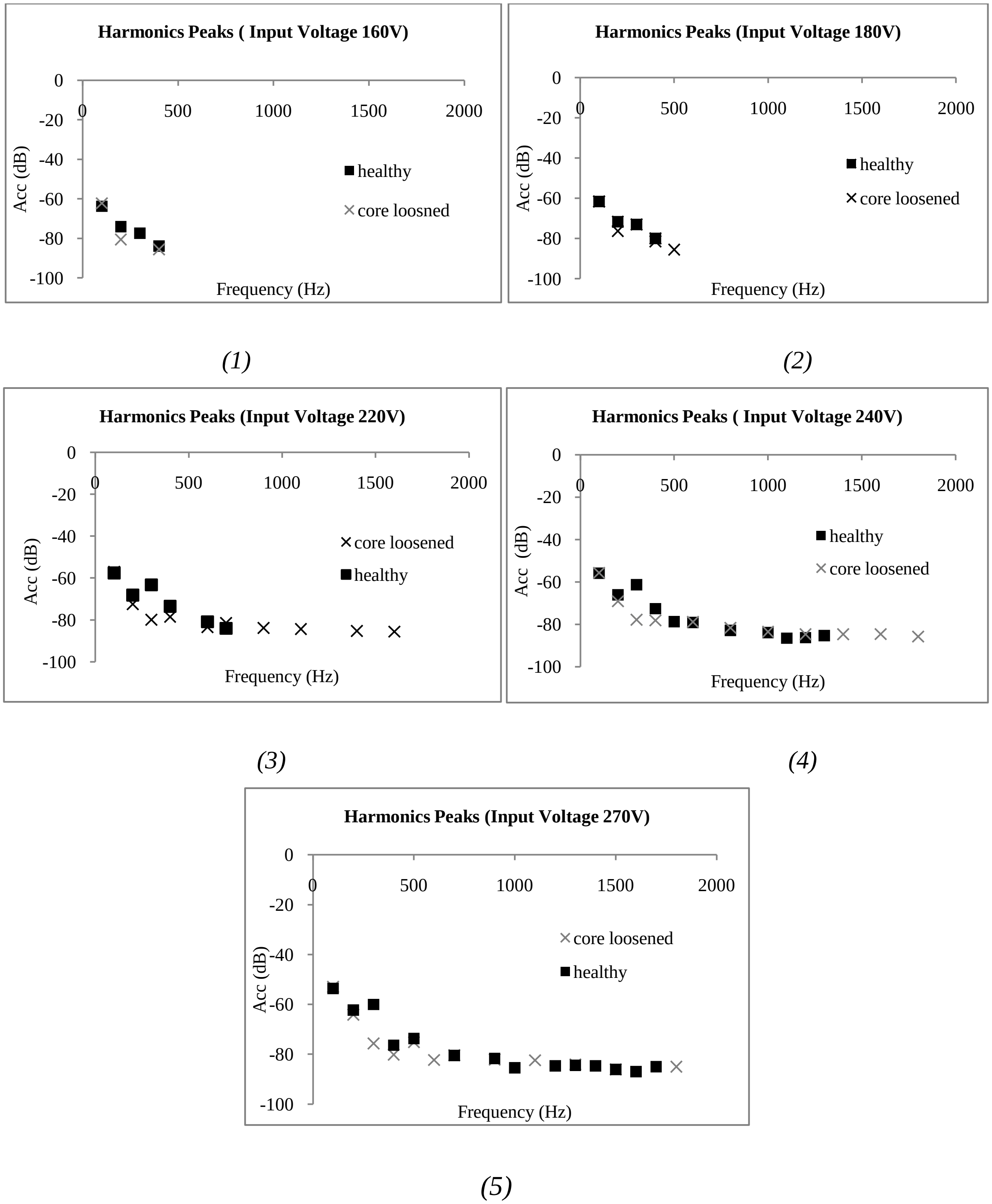


Figure 4.8-5 Core Vibration when the Input Voltage is 160V, 180V, 220V, 240V and 270V

Figure 4.8-5 shows the vibration harmonics peaks of a healthy transformer and one with five pieces of core removed when the input voltage is 160V, 180V, 220V, 240V, and 270V respectively. From the above graphs, we find out that

(1) At low frequencies (0-1000Hz), vibration level of the transformer with five pieces of core removed is very close to that of a healthy transformer.
(2) The difference of vibration results of the two transformers shows at high frequencies. When the input voltage is larger than 220V, at high frequencies (above 1000Hz), the transformer with the core loosened has more harmonic peaks than a healthy transformer does.

4.8.5 Discussion of Test 4.8

(1) The input voltage clearly affects the vibration level of power transformers. The vibration level increases with the input voltage increases.

(2) The peak harmonics at 100Hz and its multiples are observed.

(3) Removing five pieces of core, the vibration result is different from that of a healthy transformer. At high frequencies, the transformer with core loosened has more harmonics than the healthy one does. It illustrates that the structure of the core does have effect on the transformer's vibration result. It also indicates that vibration monitoring is a valid technique for transformer failure diagnosis.

4.8.6 Winding Vibration Test

The winding failures like distortion and looseness could be directly reflected in the vibration results. That is to say, vibration test on windings is a method to detect those winding failures. However, the vibration of windings of small transformers are not visible (see Appendix1), this thesis also conduct winding vibration tests. The results show no visible vibration on the windings. It indicates that the vibration of test transformer windings is not detectable. It concluded that the winding vibration test was not valuable for this thesis. That is reason why this part was not included in this thesis.

Chapter 5 Analysis of Experimental Results

In this chapter, the previous experimental results are analysed and mathematical models of test transformers are developed. There are three parts in this chapter: the voltage/ voltage and voltage/ current relation of test transformers, the heat transfer model of test transformer windings, and the analysis of the core vibration of the test transformers.

5.1 A Summary of Test Results from Chapter4

A summary of the test results from Chapter 4 is presented in Table 5.1-1 and Table 5.1-2.

Table 5.1-1 Summary of Test Results (A)

Tests	**Relationship Explored**	**Summary of Test Results**
1	Input voltage with Output voltages (Vi-Vo)	(1)The relationship between the input voltage and output voltage is linear. (2)The V_i/V_o relation does not change much at different ambient temperature. In other words, the V_i/V_o is independent to the environmental temperature.
2	Input voltage with Primary current (Vi-Ip); Output voltage and Secondary current (Vo-Is)	(1) The primary current increases as the input voltage increases. (2) The relationship between the secondary current and output voltage is linear. (3)The ambient temperature change does not affect the transformer currents. (5)When the loading is small enough, the relation of primary current and input voltage is linear. It means the input impedance of the transformer at 50 Hz is a constant. (6)The results reveal that increasing temperature by 20°C is not sufficient to change the condition of winding insulation.

Table 5.1-2 Summary of Test Results (B)

Tests	Relationship explored	Summary of Test Results
3	Input voltage with winding temperatures (Vi-Tp & Vi-Ts)	(1) The winding temperature shows fluctuation around the environmental temperature. (2) In the measurement, the transformer is not damaged.
4	Input voltage with Primary current (Vi-Ip); Output voltage with secondary current(Vo-Is)	(1) The relation of primary current and input voltage is almost linear. (2)The HID bulb changed its resistance according to the current change, so the relation of secondary current and output voltage is not linear.
5	Winding temperatures with time (Tp & Ts with time)	(1) Winding temperature increases slowly with time. (2) Ambient temperature change (20°C-40°C) does not affect the winding temperature when the transformer is not overloaded. (3) The thermal fuse installed in the transformer protects the transformer from destroying from overloading.
6	Find out the relationship of overheating or short circuit failure modes with winding temperatures, currents	(1) Overloading is replicated in the laboratory successfully. (2) The reflections of overlading are the current value and the winding temperature value increase. (3) It results in the short circuit failure. (4) The test shows the outer turns has higher temperature, which is not correspondent with the knowledge of heat transfer.
7	Identify the role of Oxygen in test 6	(1) The outer turns of primary windings burned instead of the inner turns, because of the existence of the oxygen. (2) There is no visible damage of the wire.
8	Input voltage with vibration (Vi-vibration)	(1) The input voltage clearly affects the vibration level of power transformers. The vibration level increases with the input voltage increases. (2) The peak harmonic shows at 100 Hz. (3) Removing five pieces of core, the vibration result is different from that of a healthy transformer. At high frequencies, the transformer with core loosened has more harmonics than the healthy one does.

From these results, the Vi/Vo, V/I relations of test transformer, thermal dynamics of winding heat transfer and the vibration of test transformer are modelled and analysed in the following sections.

5.2 Transfer Function of Test Transformer

5.2.1 Transfer Function in Voltage

Theoretically, for ideal transformer (Harlow, 2007),

$$U_1/U_2 = N_1/N_2, \tag{5-1}$$

where N_1 and N_2 are the turns of the primary and secondary windings, U_1 and U_2 are the voltages applied on the primary and secondary circuits. The ratio U_1 of U_2 is defined as $H_{(V)}$.

$$H_{(V)} = U_1/U_2, \tag{5-2}$$

For the first transformer in the overloading test, the turns of the winding is N1=818; N2=87. In this case, N_1/N_2=818/87=9.402. Therefore, the $H_{(V)}$ of the test transformer is 9.402 theoretically.

The experimental result (Input voltage VS Output voltage relationship test, see 4.1) and theoretical result are compared in Figure 5.2-1.

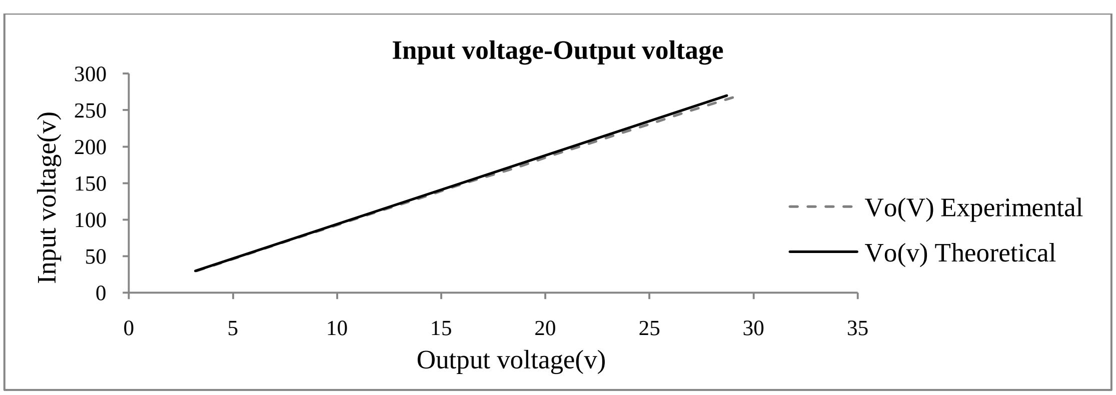


Figure 5.2-1 H (V) of the Test Transformer

Figure 5.2-1 shows that the theoretical result agrees with the experimental result. Thus the ideal transformer assumption is reasonable.

5.2.2 The Mechanism of Overloading Test

In test 4.6, the secondary circuit is shorted, measure the input and output voltages, primary and secondary currents, we obtained the results of the primary and secondary currents in Figure 5.2-2.

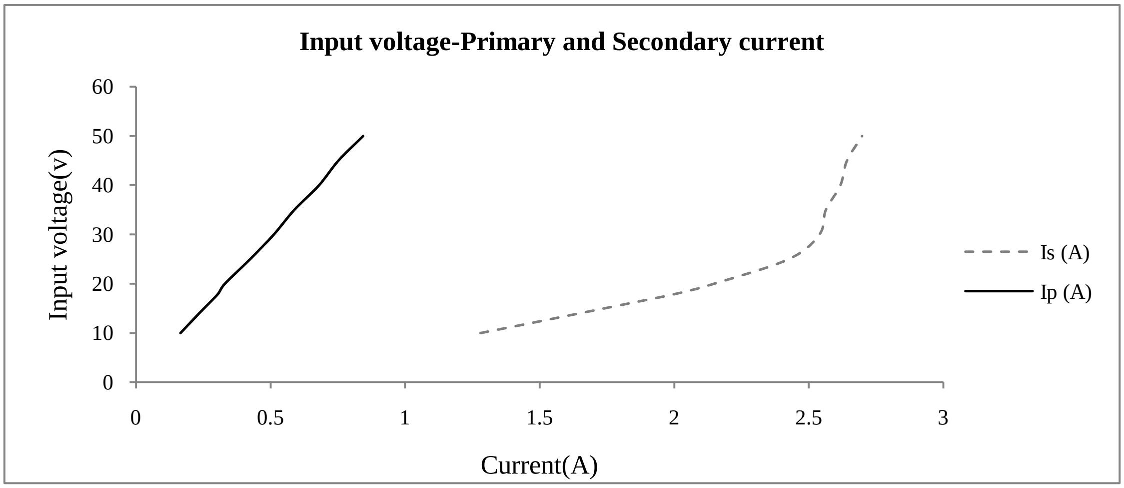


Figure 5.2-2 Input Voltage-Primary Current and Secondary Current

Figure 5.2-2 shows the primary and secondary current changes with the input voltage when the secondary winding is shorted. This is from a healthy transformer. The primary and secondary windings turns are 798 and 65 respectively.

The primary current is almost linear, but the secondary current is nonlinear since the input voltage exceeds 20V. This might due to the saturation of the magnetic field.

From the test results, we found that when the input voltage Ui=20V, the secondary current Is =2.147A; Then the magnetic flux density

$$B = \mu_0 \mu_r N I \tag{5-3}$$

Where, μ_0 is the permeability of the free space. $\mu_0 = 4\pi \times 10^{-7}$ H/m ; μ_r is the relative permeability. For FeSi (Si 3-4.5%), μ_r=10000; N is the turns of the winding; N=N_2 =65; I is the current through the winding; I=Is=2.147A;

Therefore, $B = 4\pi \times 10^{-7} \times 10000 \times 65 \times 2.147 = 1.76T$

According to the published data, the saturation magnetic flux density Bs of the FeSi core is around 1.2-1.7T. Therefore, the magnetic field saturated and the secondary current with input voltage is not linear after that point.

5.3 Heat Transfer Model of Test Transformer Windings

In the overloading test, time-winding temperatures curves are obtained (Figure 4.2.6). From this result, this thesis builds a heat transfer model for the windings when the transformer is overloaded.

Suppose Q is the total energy the current generated; Q' the energy loss from the winding to the environment; E is the energy used to increase the winding temperature.

$$Q = I^2Rt \qquad (5\text{-}4)$$

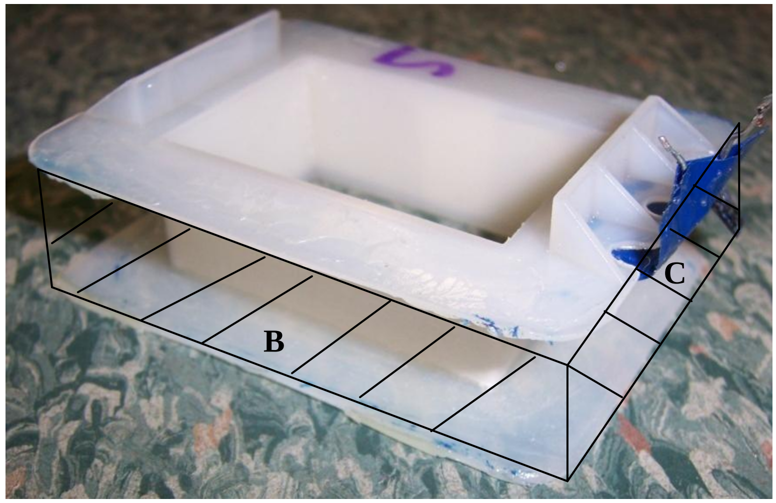
where, I is the current through the winding; R is the resistance of the winding and t is the operating time.

In this case, the heat transfer type is convection.

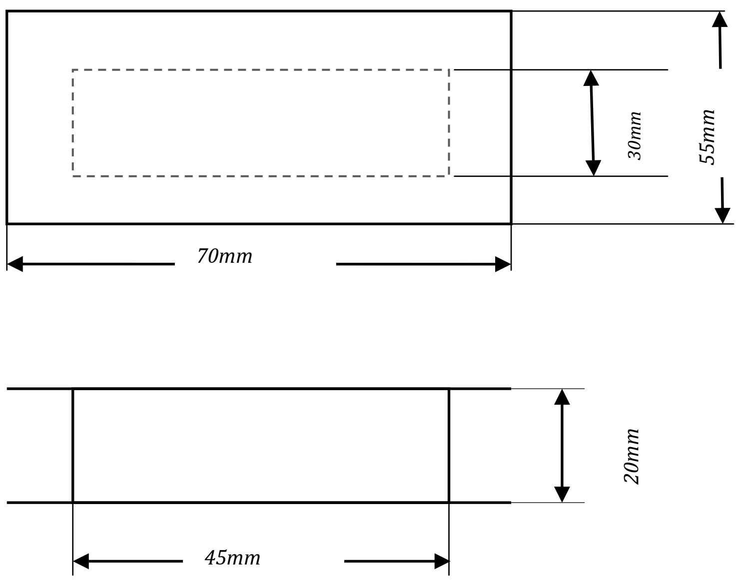
$$Q' = hA(T_H - T_b) \qquad (5\text{-}5)$$

where, A is the surface area; h is the heat transfer coefficient; is the T_H is the surface temperature; Tb is the ambient temperature; and t is the time.

The outlook and dimensions of the winding former is listed in Figure 5.3-1



(1)



(2)

Figure 5.3-1 Outlook and Dimensions of the Frame of Windings

The heat transfer area is double of area C and half of area B (marked in Figure 5.3-1), as half of B is covered by the core. Thus, the heat transfer surface area

$$A = 2 \times 55 \times 20 + 2 \times \left(\frac{1}{2} \times 70 \times 20\right) = 360 \times 10^{-6} m^2$$

$$E = km(T_w - T_b), \quad (5\text{-}6)$$

where, E is the energy used to increase the windings' temperature; k is the heat capacity of the winding; m is the mass of it; Tw is the temperature of the winding and Tb is the ambient temperature.

$$E = Q - Q', \qquad (5\text{-}7)$$

Then we obtain

$$km(T_w - T_b) = I^2Rt - hA(T_H - T_b)t \qquad (5\text{-}8)$$

where, k= 420 J/(kg.°C); Rp=20Ω; Rs=0.70Ω;

$$m = \rho SL \qquad (5\text{-}9)$$

where, ρ is the density of copper, $\rho = 8.9 \times 10^3 Kg/m^3$; S is the cross section area; L is the length of the winding;

For the primary winding, Φ=0.42mm;

For the secondary winding, Φ=1.84mm;

h= $407 W/(m^2\,°C)$

The mean values of windings' turns of the tested transformers are 800 (primary winding) and 78 (secondary winding) respectively.

For the primary winding, $\mathrm{Sp} = \frac{1}{4}\pi\Phi^2 = 0.152 \times 10^{-6}\ \mathrm{m}^2$, $\mathrm{Lp} = \frac{1}{2} \times [(70 + 55) \times 2 +$ 45+30×2×800=1.6×105mm=160m.

Where Sp is the cross section area of the wire in primary winding; Lp is the length of the wire in primary winding. We obtain:

$$90.9(T_w - T_b) = 20I_P^2t - 0.0.1465(T_H - T_b)t \qquad (5\text{-}10)$$

For the secondary winding, $Ss = \frac{1}{4}\pi\Phi^2 = 2.659 \times 10^{-6}\ m^2$, Ls=15.6m

Where Ss is the cross section area of the wire in secondary winding and Ls is the length of the wire in secondary winding. We obtain:

$$155(T_w - T_b) = 0.7 I_S^2 t - 0.1465(T_H - T_b)t \qquad (5\text{-}11)$$

Take the experimental results to Equation 5-10 and 5-11, we will obtain the temperature of the hot spot of transformer windings. For example, when the ambient temperature is at 20ºC, the input voltage is 238V, Ip=0.587A; Is=3.53A; when t=60mins, for the winding temperature, Tp=55.8ºC; Ts=58ºC. Data for this test is attached in Appendix 3.
Then we obtain for the primary winding,

$$T_{w(P)} = 20 + \frac{20\ \times 0.587^2\ \times 3600 - 0.1465 \times (55.8 - 20) \times 3600}{90.9} = 85.7°C$$

For the secondary winding,

$$T_{w(s)} = 93.3°C$$

Because in the test, some of the materials covered the windings are removed, the temperature of winding surface is much lower than that of the inner of the windings.

5.4 Analysis of Vibration Results

The observations from the vibration test in this thesis (See 4.8 vibration test) are: (1) The vibration level increases with the input voltage increases; (2) The largest vibration harmonic peak shows at 100Hz; and (3) At low frequencies, the vibration result of a core-loosened transformer is similar to that of a healthy transformer.

Transformer vibrations include core and windings vibrations. They are generated by different forces appear on core and windings. The electrodynamic forces generate the winding vibration.

The combination of electric and magnetic forces on a charged object is called electromagnetic force.

$$F = B \times I \tag{5-12}$$

where, B is the magnetic flux density at the winding . I is the current through the winding .

We also know that,

$$B \propto I \tag{5-13}$$

Then we obtain,

$$F \propto I^2 \tag{5-14}$$

It is worth noting that F is the force per unit length. The direction of the force is determined by $\vec{B}$ and $\vec{I}$.

It illustrates that the electrodynamic forces are proportional to the current squared. It also indicates that the vibration of windings is dependant to the current squared. Considering the current is sinusoidal (50Hz), the winding vibration main harmonic is that of 100Hz. Additionally, when the secondary circuit is open, the current value is zero; the vibration of windings is approximately zero.

The core vibration is generated by magnetostriction and magnetic force. Ferromagnetic materials change their shape or dimensions when they are in a magnetic field. It is called magnetostriction. The variation of material's magnetization due to the applied magnetic field changes the magnetostrictive strain until reaching its saturation value. Neglecting the hysteresis effect, the magnetostriction is approximately proportional to the elongation and the inductance squared. Considering the relation of inductance and applied voltage, ignore the leakage flux and resistance of windings,

$$u = N\frac{d\Phi}{dt} \qquad (5\text{-}15)$$

The voltage is sinusoidal, $u = U_m \sin(\omega t)$,

where U_m is the maximum value of voltage; ω is the angular frequency;

$$\Phi = \Phi_m\, sin(\omega t) \qquad (5\text{-}16)$$

where Φ_m is the maximum value of magnetic flux.

$$u = N\frac{d\Phi}{dt} = N\omega\Phi_m\, cos(\omega t) = 2\pi f N\Phi_m\, cos(\omega t) \qquad (5\text{-}17)$$

where *f* is the frequency of the voltage.

For the RMS value of voltage,

$$U = \frac{u}{\sqrt{2}} = \frac{2\pi f N\Phi_m}{\sqrt{2}} \approx 4.44 f N\Phi_m = 4.44 f N B_m S \qquad (5\text{-}18)$$

The magnetostriction is proportional to the applied voltage squared. It reveals the relationship of the input voltage and vibration level of the core. The vibration level increases with the input voltage increase. The applied voltage is sinusoidal (50Hz), so the main harmonic of core vibration is that of 100Hz.

The magnetic flux density B in the core is

$$B = \frac{\Phi}{A} = \frac{U_m}{N_1 A\omega} cos\omega t \qquad (5\text{-}19)$$

Where Φ is the magnetic flux; A is the section area of the magnetic flux.

The magnetic field intensity H is

$$H = \frac{B}{\mu} = \frac{B}{B_S} H_c = \frac{U_m}{N_1 A\omega B_S} H_C \cos\omega t \qquad (5\text{-}20)$$

Where Bs is the saturation magnetic flux density; Hc is coercive force.

The magnetostriction is represented by the magnetostriction coefficient ε.

$$= \frac{\Delta L}{L} = \frac{2_S}{H_C^2}\int_0^H |H|\, dH = \frac{s}{H_c^2} H^2 = \frac{_sU_m^2}{(N_1 A\omega B_S)^2} cos^2\omega t \qquad (5\text{-}21)$$

Where L is the original size of the silicon steel sheet; ΔL is the distortion of the silicon steel of the core.

It reveals that the vibration of core is proportional to the voltage square and the fundamental frequency is double that of the voltage. That is to say, the fundamental frequency of core vibration is 100Hz.

Chapter 6 Conclusions and Future Work

6.1 Conclusions

This thesis generated failure modes for overheating, short circuit and core deformation in a safe and repeatable manner in the laboratory. It designed tests to observe factors that affect the performance of a small laboratory-scaled transformer. By analysing the test results, this thesis developed models for overheating, short circuit and core deformation.

In the introduction part, this thesis proposed four objectives listed following.

(1) Initiate specific winding failures in a safe and repeatable manner in the laboratory

This thesis defined the following parameters: input and output voltages, primary and secondary currents, winding temperatures, and vibration as variables that represent the performance of transformers. It also identified three failure modes of interest: overheating in the windings, short circuit in the primary winding and core looseness by conducting a FMEA.

Based on the failure modes defined in the thesis, it developed a series of experiments. To safely conduct these tests, a safety management plan was developed. The experiments conducted on a healthy transformer, an overloaded transformer and a transformer with core loosened.

(2) Observe the behaviour of the transformer failures

There were eight tests for the three types of transformers. The test results support the view that the variables defined in this thesis can indicate the performance of the transformer. There were significant and clear observations of the transformer failures.

The overloading test induced overheating, short circuits failures. It also showed the effect of time on the winding temperatures when the transformer was overloaded. A thermal model of the heat transfer of transformer windings was developed. By monitoring the temperature of the winding surface and the current through the windings, the hot spot temperature can be calculated. Before the hot spot temperature reaches too high to generate an overheating or short circuit failure, actions can be taken to prevent losses of transformers. This is a reliable, non-contact method to prevent overheating and short circuit occurring.

The core-loosened test was used to observe the vibration level of the test transformer. Due to the magnetic forces and magnetostriction, the vibration level increased with the input voltage increased. The main harmonic frequency of the transformer vibration was at 100Hz. Some harmonics appeared multiple 50Hz due to magnetizing current. It also showed the core looseness and subsequent transformer structure change made the vibration level changes. At low frequencies, the vibration result of a core-loosened transformer was not significantly different from that of a healthy one. At high frequencies, the vibration result of the transformer with core loosened had more harmonics than that of a healthy one. This appearance of additional harmonics is a potential criterion to identify the core-looseness failure of a transformer.

By monitoring these parameters, we can diagnose and predict the transformer failures as overheating, short circuit and structure deformation or movements.

(3) Explore the influence of environmental factors that may accelerate the failure progression

The environmental factor in this thesis is the ambient temperature. Test 4.1 to test 4.3were of a healthy transformer under different ambient temperature (20ºC & 40ºC). This thesis compared the voltage/voltage, voltage/ current and voltage/ winding temperature results at different ambient temperatures (20ºC & 40ºC). It indicated that the change of 20ºC ambient temperature is not sufficient to affect the performance parameters of test transformers.

(4) Observe the behaviour of the tested transformer under different conditions

The results of this thesis support the view that

(1) Change of ambient temperature (20º C change in this case) is not sufficient to affect the transformers' performance;

(2) The overloading condition is sufficient to generate overheating or short circuit failure modes; and

(3) The change of the structure of transformers resulting from core-looseness has effect on the transformer vibration results.

This thesis started with studying the failure modes, causes and effects of power transformers. It concluded three main failure modes of power transformers. Hence it replicated the failures on small transformers in laboratory, obtained the behaviours of test transformer, and the affected factors. Finally, these results reached the conclusions above. In the application of maintenance of power transformers, this gives the idea of considering these findings and properly monitoring the factors studied in this thesis might be useful to give the users the status of power transformers and help them in diagnosis and maintenance decision making. This part is not the work of this thesis. It initiates future work of this project. The project will finally effectively prevent power transformer failures and decrease the cost of maintenance.

The main contribution of this thesis is that it originally developed procedures of testing small laboratory scaled transformers and replicated transformer failures in a safe and repeatable manner in Lab. One of the findings of this thesis reveals the effects of ambient temperature change on the transformer performance. It built thermal model for the heat transfer of transformer windings through which the hot pot temperature of transformer can be calculated. It analysed the vibration of the core and pointed out that at high frequencies, the vibration results are affected by the change of core structure.

6.2 Future Work

6.2.1 Bayesian Belief Network

This thesis generates several failure modes of power transformer. It also defines the possible reasons. Using these data, models can be developed to associate failures with causes and to use statistics to predict the failure of power transformers.

BBN (Bayesian Belief Network) may be a suitable approach for future projects due to their ability to combine a set of random variables and their causal dependencies and providing a flexible structure for modelling and evaluating uncertainty. A Bayesian Causal Network is a mathematical model of the cause and effect relationships and the way these relationships lead to observed statistical patterns of an event. It can be presented in Figure 6.2-1.

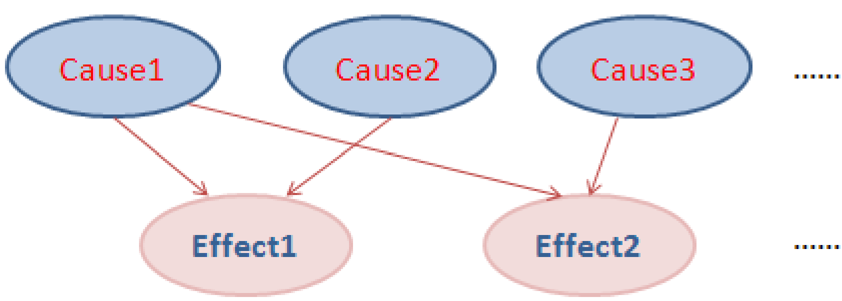


Figure 6.2-1 Bayesian Causal Network

Using the reliability data from the tests in this thesis, a causal Bayesian network which shows the relationship between factors and failure modes will be built by a future student. The aim is to diagnose failure modes by monitoring the factors of interest and, leveraging knowledge of previous failures, predict the remaining useful life of power transformers.

6.2.2 Extend the Model to Large Scale Transformers

This thesis design and conduct tests applied on small power transformers in laboratory scale. However, large-scale power transformers are the main concerns in the field. Therefore extending the application of this thesis to large-scale power transformers is practically important.

Laboratory tests on large-scale power transformers are difficult to conduct due to safety considerations so future work will rely on field failure data from manufacturers and operators. University researchers will conduct condition monitoring tests. These field tests include tank vibration test, currents, voltages tests, and winding temperature tests. Data from these tests will be used to develop a BBN model for large-scale power transformers condition assessment and life prediction.

Appendix 1 – Test of Handmade Transformers

This part contains building transformers and tests these handmade transformers. Building transformers requires appropriate components of transformers. These components are core, winding materials and a frame for forming windings. Testing these handmade transformers is to identify the indicators of the performance of transformers. The performance refers to the transfer function, efficiency. In this thesis, it refer to the input and output voltages of the transformer, the primary and secondary winding temperature, the primary and secondary winding currents, and the accelerometer of the core.

1. Aim of the Transformer Building and Test

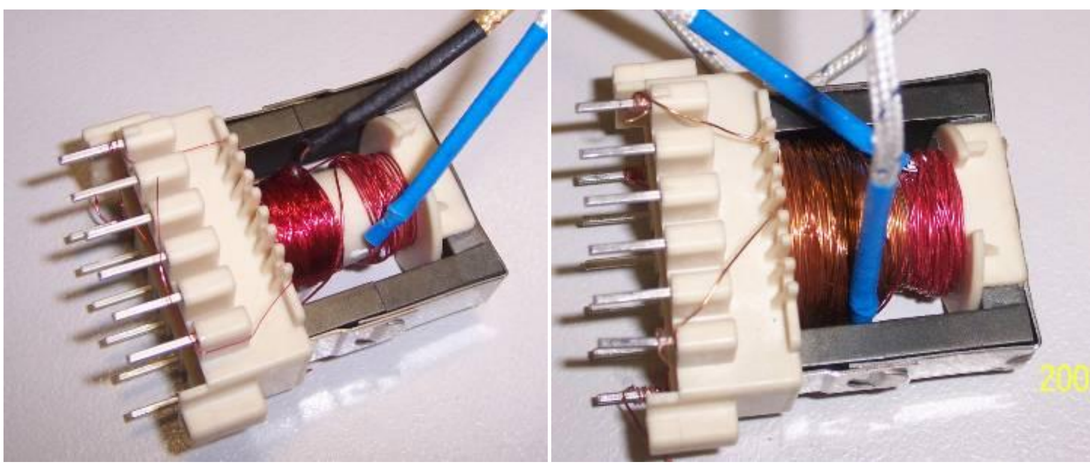
The aim of this part is to identify the properties and the indicators of the transformer defined in the previous reliability test plan: input and output voltages (Vi, Vo), primary and secondary winding temperature (Tp, Ts), primary and secondary winding currents (Ip, Is), and accelerometer of the core (Acc). By doing this, we can obtain the measurable variables and test conditions of the reliability tests of power transformers.

2. Building Transformers

Five transformers are built in this part. The specifications of these transformers are showed in Table A-1. The handmade transformers are shown in Figure A-1. These handmade transformers are labelled as No.1, 2, 3, 4, and 5.

Table A-1The Materials Used for Building Each Transformer

No.	Core Material	Windings Materials	Ratio	Turns
1	RS Components 231-8656	Ø0.14 & Ø0.35 copper wire	8:1	160:20
2				320:40
3	#1 core			640:80
4	#2 core	Ø0.25& Ø0.35 copper wire		320:40
5	#2 core	Ø0.25& Ø0.35 copper wire		320:40



No. 1, 2, and 3 No. 4 and 5

FigureA-1 the Hand Made Transformers

Table A-1 shows the specifications of the materials of the handmade transformers. These materials are obtained from the local market. Most of the small power transformers we can find in local market have the ratio around 8:1. Therefore, the ratio of transformers is defined as 8:1. Figure A-1 shows the product of the handmade transformers.

3. Transformer Tests

The tests include five parts:

(1) Input-Output Voltage Test (Vi-Vo test).

(2) Primary and Secondary Current Test with Different Input Voltage (Ip-Vi, Is-Vo tests).

(3) Winding Temperature Test with Different Input Voltage (Tp-Vi, Ts-Vo tests).

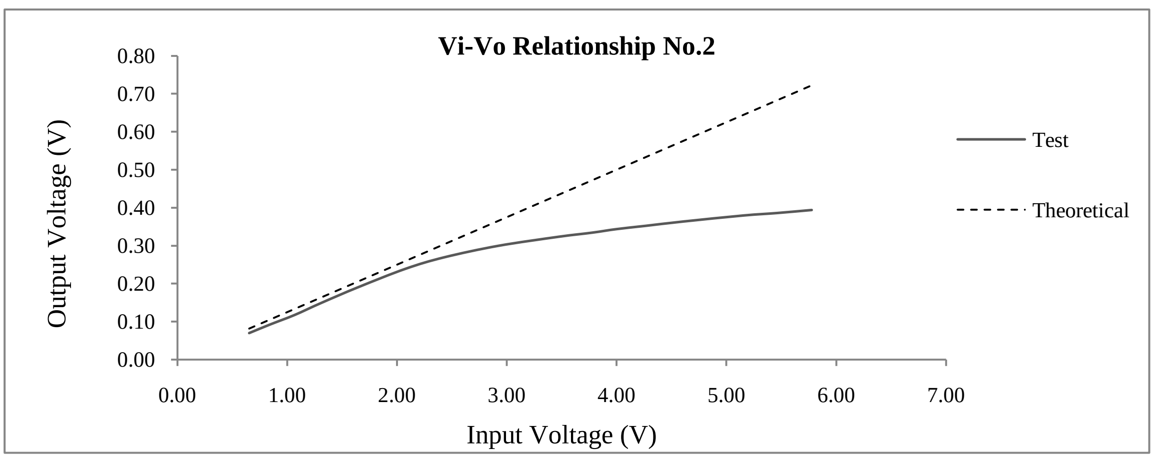
(4) The Vibration Test with Different Input Voltage.

(5) A temperature test with steady input voltage and a high frequency test.

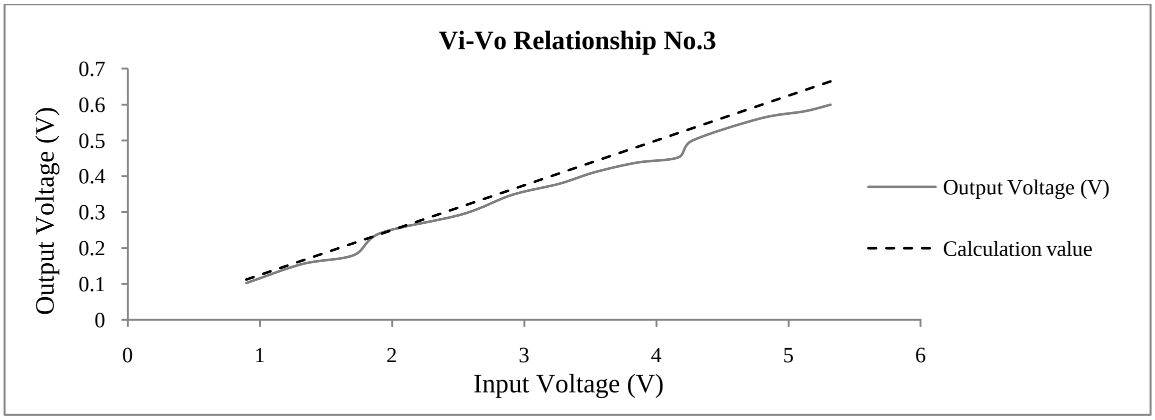
3.1 Test Results

3.1.1 Vi-Vo Relationship Test

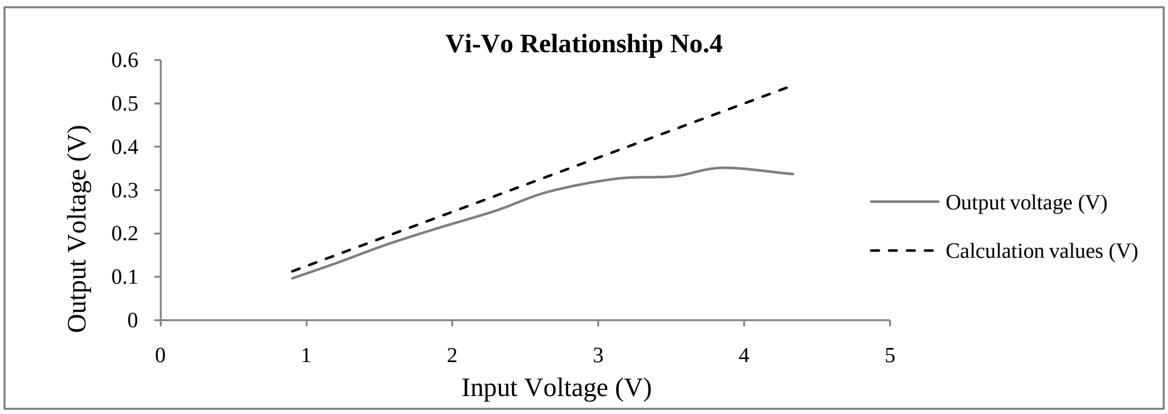
This test is to find out the Vi-Vo relationship of the handmade transformers. In this test, the transformers are supplied with 0-24V AC power. The Vi and Vo are measured respectively. The relationship between them is shown in Figure A-2.



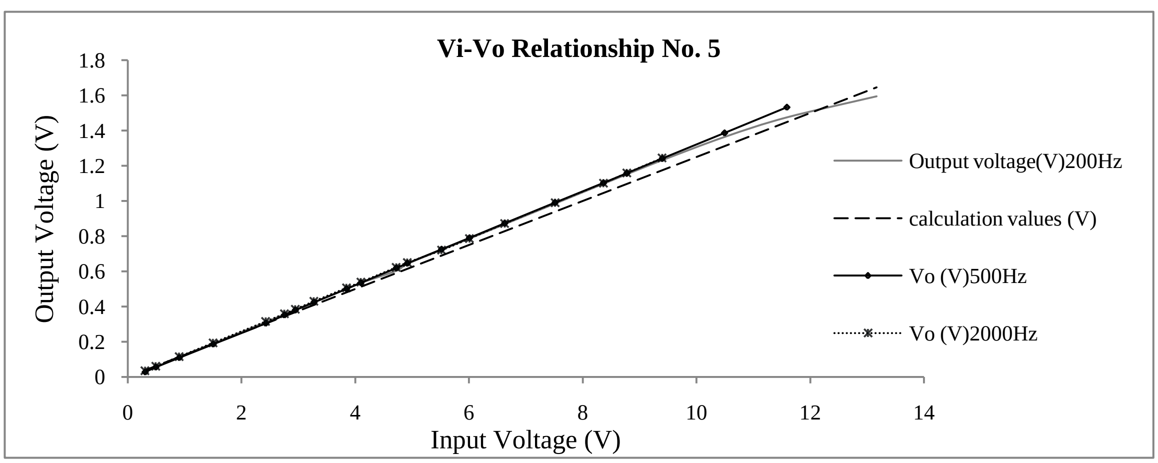
No.2 Transformer



No.3 Transformer



No. 4 Transformer



No. 5 Transformer

Figure A-2: Output-Input Voltage Relationship Curves

The results show the relationship of Vo and Vi of different handmade transformers. From the table above, we observe:

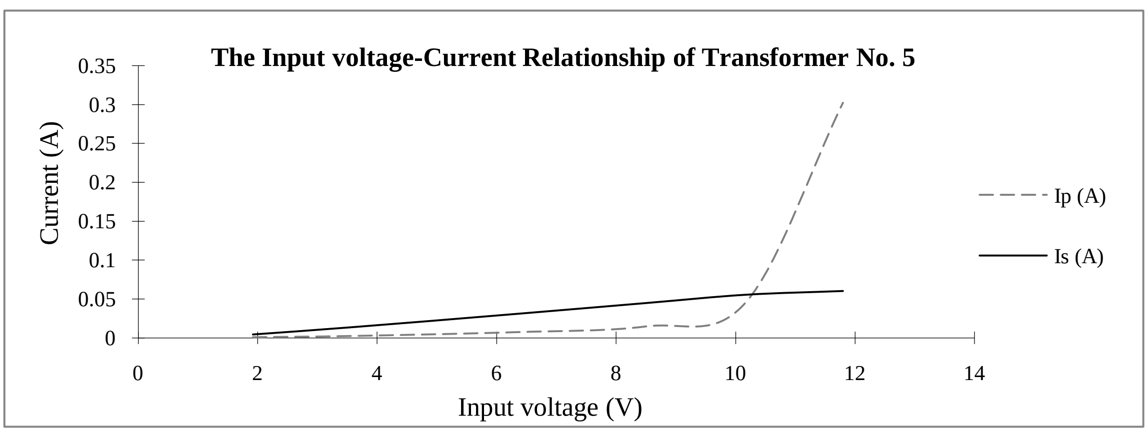
(1) When the Vi is larger than 2V, the transformer is nonlinear.

(2) When the Vi is larger than 5V, there is a burning smell of the winding and Tp is over 60°C.

(3) At 200 Hz, the transformer becomes nonlinear when the Vi is larger than 10V. At other frequencies, the transformer is linear when the Vi increases to over 20V.

3.1.2. Current-Input Voltage Relationship

This test is to identify the change of Ip and Is when the Vi changes. It is also to identify whether the winding current can be an indicator of the transformer's performance. This test provides these handmade transformers 0-24V AC input voltage. The Ip and Is are measured. Figure A-3 shows the results of the change of Ip and Is with the input voltage changes.



Transformer No.5

Figure A-3 The Currents with Input Voltage Relationship

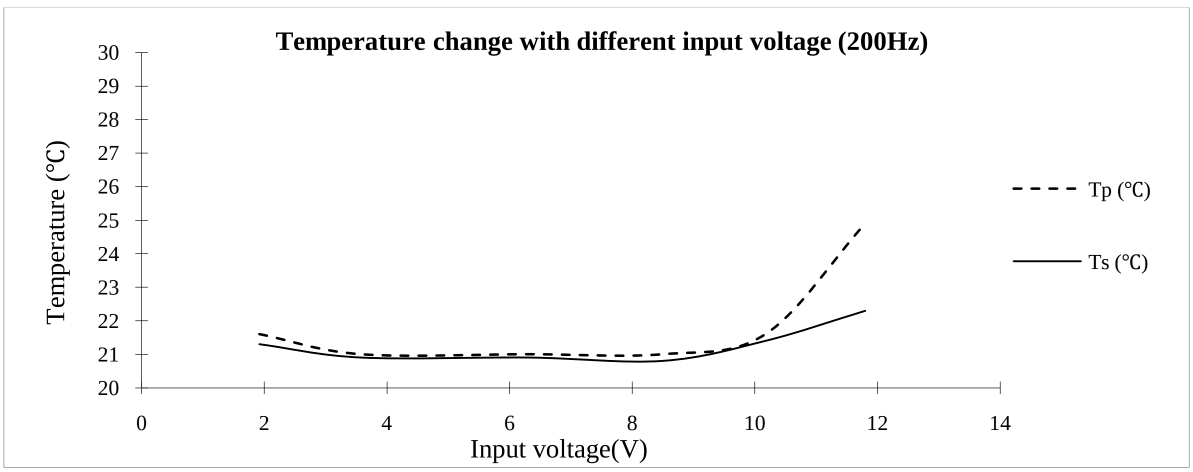
In Figure A-3, the dash curves in the graphs represent Ip while the solid ones represent Is. We observe:

(1) Obviously the current changes when the input voltage changes.

(2) When the transformers reach the magnetic saturation, the primary current has a dramatic increase.

3.1.3. TEMP-Input Voltage Relationship

This test is to identify the temperature change with the input voltage changes. It is also to identify whether it can be an indicator of the transformer's performance. This test is set up as the previous two tests. The primary winding temperature (Tp) and secondary winding temperature (Ts) are measured by an infra temperature gun. Figure A-4 shows the relationship between the winding temperature and input voltages.



No. 5 Transformer

Figure A-4: TEMP-Input Voltage Relationship Curves

In Figure A-4, the dash curves represent the temperature of the primary winding. The solid ones represent that of the secondary winding or the environmental temperature. We obtain: The Primary winding's temperature increases faster than that of the secondary winding.

3.1.4. Vibration Test

The vibration test is to identify the vibration level of these handmade transformers. It is measured on the core and windings of No.4 and No.5 transformers. The results are shown in the table below.

TableA-2 Vibration Results

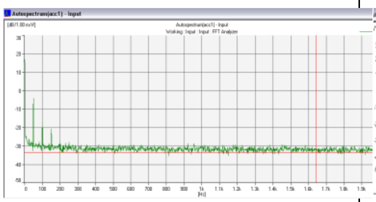
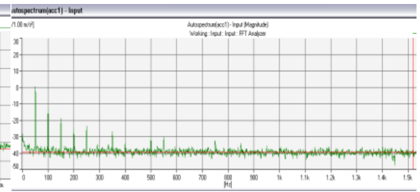
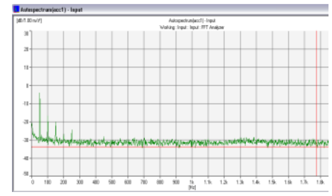
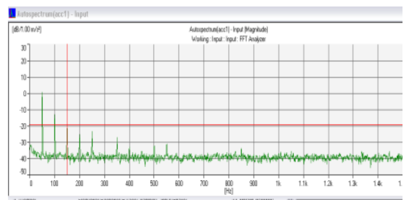
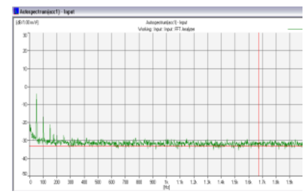
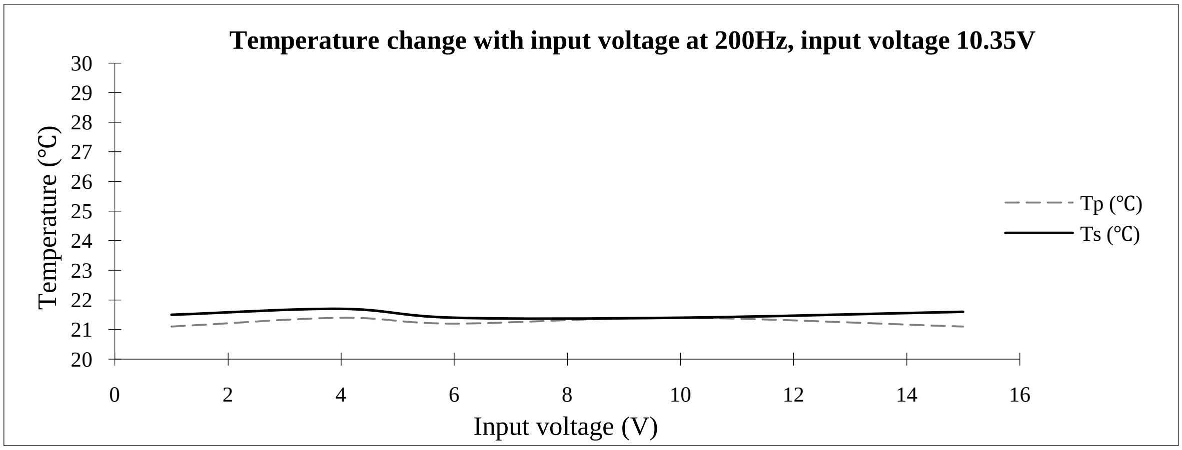
Back ground	Measured on the winding	Measured on the core
	 Lower input voltage	 Lower input voltage
	 Higher input voltage	 Higher input voltage

Table A-2 shows the vibration results when the transformer is under a lower inout voltage (2V) and a higher input voltage (10V).

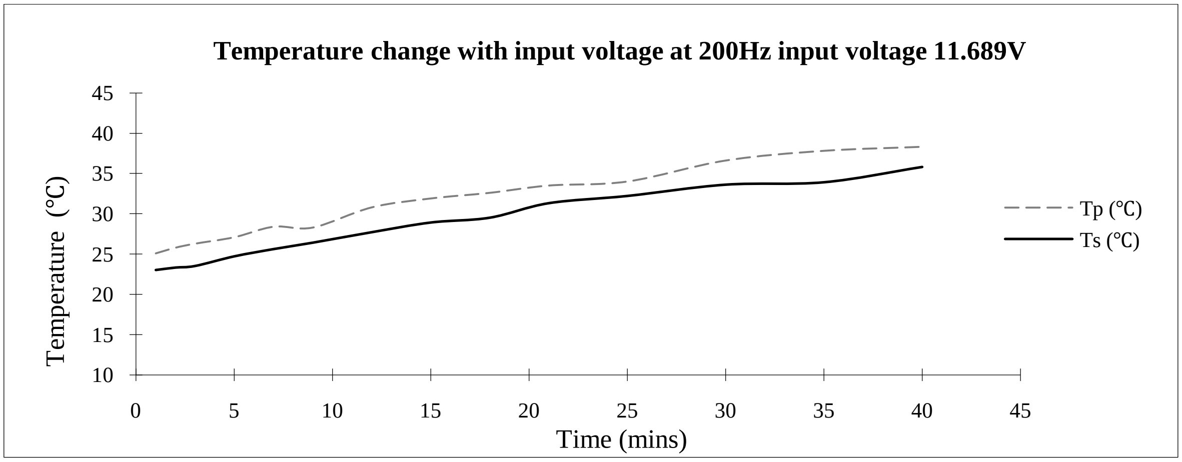
The harmonics on these results are possibly of the electrical signal. The vibration of the transformer is not detected.

3.1.5. Temperature Change with Steady Input Voltage

This test aims to identify the temperature change with the input voltage keeps at some steady values. The No. 5 transformer is given 10.35V and 11.69V input voltage respectively. The temperatures of primary and secondary windings are measured every 5 minutes. Figure A-5 shows the change of the winding temperatures.



Input voltage is 10.35V



Input voltage is 11.69V

Figure A-5: Curves of Temperature Change with Steady Input Voltage

In Figure A-5, the dash curves are the change of the temperature of the primary winding while the solid ones are that of the secondary windings.

When the input voltage is 10.35V, the primary current is measured 0.054A while the secondary current is 0.0530A. The ambient temperature is 20.9°C. The temperatures of the primary and secondary winding keep steady.

When the input voltage is 11.689V, the primary current is measured 0.2801A while the secondary current is 0.0607A. The ambient temperature is 20.9°C. The temperatures of the primary and secondary winding have a clear increase.

3.2 Test Conclusions

All the tests of the handmade transformers indicate that:

(1) The input-output voltage relationship, the winding current, temperature could represent the performance of the small transformer. These are indicators of the transformer's performance. The test indicates that the winding temperature and working time are indicators of transformer's performance.

(2) The vibration of small handmade transformer is too small to detect. It may due to the current is too small to generate a measurable vibration.

Appendix2 – Risk Assessment of Small Transformers Failure Causes and Effects Estimation

1. Project Outline

This project is to develop and test processes that reveal the relationships between (1) transformer faults that result in some specific failures, (2) vibration measures that track the degradation resulting from the initial fault, and (3) other outside factors (heat, load, input voltage) that may accelerate the fault progression.

2. Description of the Experimental Process

The tests are executed in Laboratory G 17.

2.1 Circuit Diagram and Component Layout

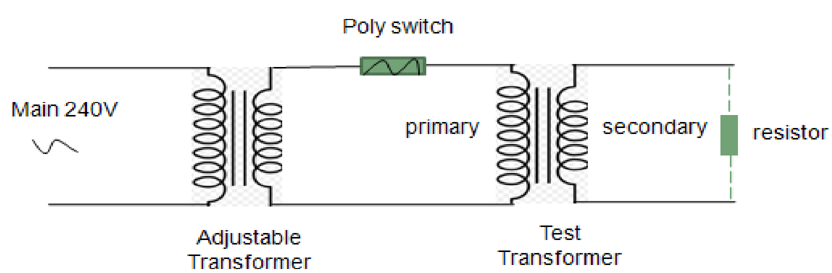


Figure A-6.Test Circuit Diagram

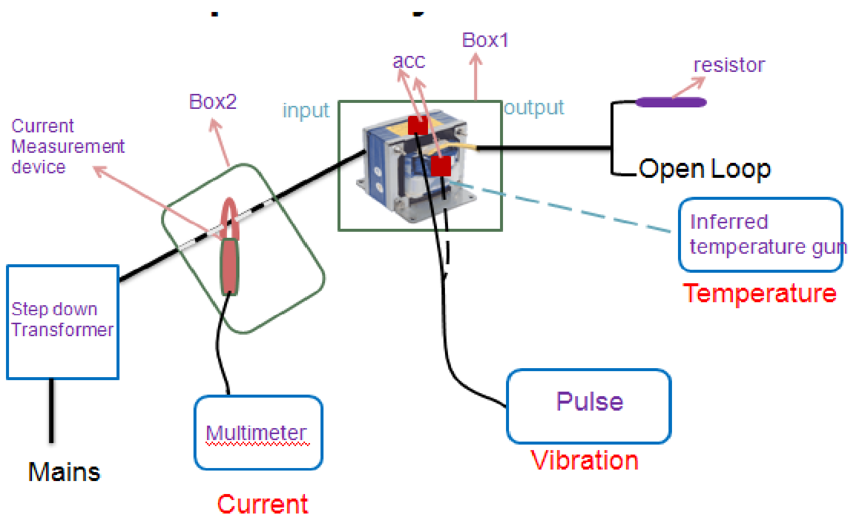


Figure A-7 Test Component Layout

In Figure A-7, adjustable Transformer is changed to Autotransformer 'Variac'.

In Figure A-7 the Step down Transformer is changed to variac and change Pulse to Dynamic Signal Analyser.

2.2 Experimental Setup

The first step is testing the new good transformer under 20°C. The input voltage varies from 0 to 240V, and the primary current, winding temperature and vibration of winding and core will be measured.

The transformer temperature is increased to 40°C. The input voltage is varied over the range 0 – 240V and the same variables as in Step 1 are measured.

In step 3, there will be some damages to the transformer. The damage is the looseness of the winding and core. The environmental temperature and input voltage will also change [(20°C &40°C), (0-240V)].

3. Task Hazard Identification

The proposed research project has been reviewed and the following potential safety hazards have been identified:

Risk of electrocution or serious injury as the result of contact with live or damaged single insulated live 240V electrical circuits. This is the result of researchers working on the primary circuit of mains operated transformers and having direct contacts with mains 240 V supplies.

Risk of electrocution or injury from unexpected or unpredictable changes to the insulation integrity of the experimental circuit as the result of mechanical or environmental changes deliberately induced to electrical components to induce premature failure.

Risk of fire or toxic fume generation as the result of overheating electrical components from induced failure or the heating of the experiment using an electric heater.

Working alone with exposure to all of the hazards identified above.

4. Job Safety Analysis

Table A-3 lists the procedures of safety analysis in this assessment. The potential hazards of the test and consequences are discussed. The Corresponding safety management methods are also presented.

Table A-3 Job Safety Analysis

Step	Hazard	Consequences	Safety Management
1	1) Electrocution from 240V mains potential	Death or serious injury	1) Every step of the process must have two layers of insulation to ensure isolation from hazardous voltages 2) In situations where double insulation is not possible, then electrical isolation will occur
2	1) Electric heater 2) Short circuit on transformer	1) Burns from fire or ignition sources 2) Injuries and damage to infrastructure	1) Keep the flammable materials away from heat and ignition sources 2) The test system is isolated when researchers are not in attendance 3) Fit a automatic cut out switch to the primary circuit that will interrupt the supply voltage when current or temperature limits are exceeded 4) No work on this project should be carried out outside of Normal Working Hours and researchers should not work alone
3	1) Decomposition of materials	1) Exposure to the inhalation of toxic vapours	1) Avoid overheating to decomposition – if this is not possible then conduct the experiment where exhaust extraction is provided

5. Emergency Procedures

In the event of electrocution ensure that the electrical supply is turned off before touching the victim. If the victim is unconscious, and there are no signs of respiration or pulse, then immediate CPR should be administered. If more than one person is present get immediate First Aid assistance from the School's First Aid Officers and phone Security on 2222. Other areas of assistance include the University Medical Centre.

Emergency assistance contact details should be on display in the laboratory where the work is taking place and an internal phone should be available.

All electrical accidents require medical follow up to ensure that the heart rhythm is stable and that there is no further risk to health.

A Confidential Accident Report must be completed immediately and submitted to the School Safety Officer or the School Safety Representative. Follow up will include an investigation by the UWA FM Electricians and Office of Energy.

In case of fire, follow the School's Emergency Evacuation Procedures.

References

(1980) Procedures for Performing a Failure Mode, Effects and Criticality Analysis. IN DEFENSE, D. O. (Ed.) MIL-STD1629A.

(1991) IEEE Guide for Failure Investigation, Documentation, and Analysis for Power Transformer and Shunt Reactors. IN STANDARD, A. N. (Ed.) IEEE C57.125-1991.

(2000) Surface Vehicle Recommended Practice. IN US, D. O. D. O. (Ed.) SAE J1739.

(2007) IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems. IN STANDARD, A. N. (Ed.) IEEE Std 493-1997.

(2008) Analysis Techniques for System Reliability-Procedure for Failure Mode and Effects Analysis (FMEA). IN AUSTRALIA, S. (Ed.) AS IEC 60812-2008.

ABB (2004) Instrument Transformers-Technique Information and Application Guild.

ADMINISTRATION, U. S. E. I. (2010) International Energy Outlook. IN ENERGY, U. S. D. O. (Ed.). Washington, DC.

ANDERS, G., OTAL, S. & HJARTARSON, T. H. (2006) Deriving Asset Probabilities of Failure: Effects of Condition and Maintenance Levels. Power Engineering Society General Meeting, 2006. Montreal, Que.

ARSHAD, M. & ISLAM, S. M. (2006) A Novel Fuzzy Logic Technique for Power Transformer Asset Management. Industry Applications Conference, 2006. Tampa, FL

ARSHAD, M., SYED, A. & ABJUL, K. (2004) Power Transformer Asset Management. 2004 International Conference on Power System Technology. Singapore, IEEE.

BARTLEY, W. H. (1999) An Analysis of Transformer Failures Part 1 &2-1988 through 1997

BASAK, A. (1999) Condition Monitoring of Power Transformers. Engineering Science and Education Journal, 8, 41-46.

BLOOM, N. B. (2006) Reliability Centred Maintenance, New York, McGraw-Hill Companies.

CHAIDEE, E. & TIPPACHON, W. (2011) Failure Statistics and Condition Evaluation for Power Transformer Maintenance. Power and Energy Engineering Conference (APPEEC).

CHEN, Q. & EGAN, D. M. (2006) A Bayesian Method for Transformer Life Estimation Using Perks' Hazard Function. IEEE Transactions on Power Systems, 21, 1954-1965.

CHMURA, L., MORSHUIS, P. H. F., GULSKI, E., SMIT, J. J. & JANSSEN, A. (2011) Statistical Analysis of Subcomponent Failures in Power Transformers. Electrical Insulation Conference (EIC). Maryland.

CIGRE (1983) An International Survey on Failures of Large Power Transformers in Service. Electra, 88, 21-47.

COLTMAN, J. W. (2002) The Transformer. IEEE industry applications magazine.

COSTA, S. & BRANDAO, A. F. (2004) Optimization of the Maintenance of Oil Filled Power Transformers Based on Reliability Criteria. IEEE/PES Transmission & Distribution Coference & Exposition. Latin America, IEEE.

ENRIGHT, W. G. & LAWRENCE, J. D. (Eds.) (2009) Guide to Power Transformer

Specification Issues, Christchurch, Electric Power Engineering Centre (EPE Centre), University of Canterbury.

EPRI (2006) Transformer Condition Assessment & Life Management Program. Palo Alto, EPRI.

FISHER, R. A. (1966) The Design of Experiments, London, Oliver and Boyd.

FRANZEN, A. & KARLSSON, S. (2007) Failure Modes and Effects Analysis of Transformers. Stockholm, Royal Institute of Technology, KTH School of Electrical Engineering RCAM.

FU, J. & SHAO, Y. (2006) The Experiment of Diagnosing Large-Scale Transformer Winding Looseness by FRA. East China Electric Power, 34, 28-30.

FUHR, J. & ASCHWANDEN, T. (2004) Experience with Diagnostic Tools for Condition Assessment of Large Power Transformer. 2004 IEEE International Symposium. IEEE.

FUNG, F., FUNG, K. Y. & CHAN, Y. T. (2008) Remarkable Benefit Realization by Application of Strategic Management in Power Transformer Condition Monitoring and Diagnostic System. 2008 International Conference on Condition Monitoring and Diagnosis. Beijing, China.

GAO, Z., MCCALLEY, J. & MEEKER, W. (2009) A Transformer Health Assessment Ranking Method-Use of Model Based Scoring Expert System. North American Power Symposium, 1-6.

GARCIA, B., BURGOS, J. C. & ALONSO, A. (2005) Winding Deformations Detection in Power Transformers by Tank Vibrations Monitoring. Electric Power Systems Research, 74, 129-138.

GONZALEZ, C., PLEITE, J., SALAS, R. A. & VAZQUEZ, J. (2006) Transformer Diagnosis Approach using Frequency Response Analysis Method. IEEE Industrial Electronics, IECON 2006 - 32nd Annual Conference Paris.

GULACHENSKI, E. M. & BESUNER, P. M. (1990) Transformer Failure Prediction Using Bayesian Analysis. IEEE Transactions on Power Systems, 5, 1355-1363.

HARLOW, J. H. (2007) Electrical Power Transformer Engineering, Hoboken : CRC Press.

HAYT, J., W.H.; & BUCK, J. A. (2006) Engineering Electromagnetics, Elizabeth A. Jones.

HOLSAPPLE, C. W. & WHINSTON, A. B. (1996) Decision Support Systems-A Knowledge-Based Approach, West Publish Company.

HUANG, Y., JIANG, J. & ZHAO, K. (1998) Analysis of the Reliability of 220kV Power Transformers. Transformers, 7, 12-14.

ISLAM, S. M. (2000) Detection of Shorted Turns and Winding Movements in Large Power Transformers Using Frequency Response Analysis. Power Engineering Society Winter Meeting.

JARDINE, A. K. S. (1973) Maintenance, Replacement, and Reliability, Toronto, Pitman Publishing.

JI, S., SHAN, P. & LI, Y. (2001) The Vibration Measuring System for Monitoring Core and Winding Condition of Power Transformer. Proceedings of the Symposium on Electrical and Electronic Insulating Materials and Applications in Systems, 33, 849-852.

JIN, Z., ZHU, M. & ZHU, Z. (2001) Fault Location of Transformer Winding Deformation Using Frequency Response Analysis. Proceedings of the Symposium on Electrical and Electronic Insulating Materials and Applications in Systems, 33, 841-844.

LAPWORTH, J. & MCGRILL, T. (1998) Transformer Failure Modes and Planned Replacement. IEE Colloquium. IEE.

LING, H. & WANG, S. (1995) Analysis of 110kV Power Transformer Failure Events and Short Circuit Failure Modes. Transformers, 33, 33-36.

LIU, X. & SUN, Q. (2001) Test Research on Power Transformer Winding Deformation by FRA Method. Proceedings of the Symposium on Electrical and Electronic Insulating Materials and Applications in Systems, 33, 837-840.

LORIN, P., KHANNA, P., WERLE, P. & EKLUND, L. (2010) Increase Transformer Reliability and Availability: From Condition Assessment to Site Repair. PCIC Europe 2010 Conference.

LUTHER, A. & INGLIS, A. (1999) Video Engineering, McGraw-Hill, USA.

MARSHALL, S. V., DUBROFF, R. E. & SKITEK, G. G. (1996) Electromagnetic Concepts and Application, Upper Saddle River

METWALLY, I. A. (2011) Failures, Monitoring and New Trends of Power Transformers. Potentials, IEEE, 30, 36-43.

MINHAS, M., REYNDERS, J. & KLERK, P. D. (1999) Failures in Power Transformers and Appropriate Monitoring Techniques. 11th International Symposium on High-Voltage Engineering. London UK, IEEE.

MOBLEY, R. K. (1999) Root Cause Failure Analysis, Woburn, Butterworth-Heinemann.

MOON, J. F., YOON, Y. T. & LEE, S. S. (2006) Reliability-Centred Maintenance Model to Managing Power Distribution System Equipment. Power Engineering Society General Meeting, 2006. IEEE

MORAIS, D. R., ROLIM, J. G., COSER, J. & ZURN, H. H. (2006) Reliability Centred Maintenance for Capacitor Voltage Transformers. 9th International Conference on Probabilistic Methods Applied to Power Systems. Stockholm Sweden.

MUTHANNA, K. T., SARKAR, A. & DAS, K. (2006) Transformer Insulation Life Assessment. IEEE Transactions on Power Systems, 21, 150-156.

PIERCE, L. W. (1994) Thermal Considerations in Specifying Dry-Type Transformers. IEEE Transformer on Industry Applications, 30, 1090-1098.

PLEITE, J., GONZALEZ, C. & VAZQUEZ, J. (2006) Power Transformer Core Fault Diagnosis Using FRA. IEEE Melecon 2006. Benalmádena (Málaga), Spain.

PRASAD, P. V. N. & RAO, K. R. M. (2003) Failure Analysis and Replacement Strategies of Distribution Transformers Using Proportional Hazard Modelling. Reliability and Maintainability Symposium, 2003, 523-527.

RAO, B. K. N. (1996) Handbook of Condition Monitoring, Oxford, Elsevier Advanced Technology

RIPPEN, M. (2005) Decision Support Systems.

SHU, H., SUN, X. & SI, D. (2002) A RS Approach to Founding and Maintaining ES Knowledge Base for Fault Diagnosis of Power Transformer. Proceedings of CSEE, 22, 31-35.

SINGH, J., SOOD, Y. R. & JARIAL, R. K. (2008) Condition Monitoring of Power Transformers-Bibliography Survey. IEEE Ele. Insul. Mag.

STEED, J. C. (1997) Condition Monitoring Applied to Power Transformers-A Rec Experience. London, The Institution of Electrical Engineers.

TANG, W. H., WU, Q. H. & RICHARDSON, Z. J. (2004) A Simplified Transformer Thermal Model Based on Thermal-Electric Analogy. EEE Transactions on Power Delivery, 19, 1112- 1119.

TIPPACHON, W., KLAIRUANG, N., KHATSAENG, T., TEERA-ACHARIYAKUL, N. & HOKIERTI, J. (2006) Failure Mode Distribution of Transformers in Thailand. International Conference on Power System Technology, 2006. Chongqing

US Department of the Interior Bureau of Reclamation Denver Colorado (2000) Facilities Instructions, Standards and Techniques- Transformer Maintenance.

WANG, M., VANDERMAAR, A. J. & SRIVASTAVA, K. D. (2002) Review of Condition Assessment of Power Transformers in Service. IEEE Electrical Insulation Magazine.

WANG, M., VANDERMAAR, A. J. & SRIVASTAVA, K. D. (2005) Improved Detection of Power Transformer Winding Movement by Extending the FRA High Frequency Range. IEEE Transactions on Power Delivery, 20, 1930-1938.

YU, X. Z., BIRLASEKARAN, S., YONG, Y. C. & LIM, T. F. (2000) Condition Monitoring of a Power Station. International Conference on Power System Technology. IEEE.

ZHANG, Y., XU, T. & SHI, H. (2010) Comprehensive Economic Benefit Evaluation Method of Transformer Update Based on Risk Assessment Theory. 2010 China International Conference on Electricity Distribution.