INVESTIGATING THE APPLICATION OF FREQUENCY RESPONSE ANALYSIS FOR DIAGNOSING TAP CHANGER ON POWER TRANSFORMER

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Dedicated to my parents, siblings and my beloved ones
I would like to appreciate everyone who has made contribution to the successful completion of this study. Throughout this study, I have received a lot of encouragement, advise, and help from so much parties that need to be duly acknowledged.

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ABSTRACT

Electrical distribution power transformers operate on transmission and distribution systems which require different voltage levels. A sufficiently constant level of grid potential is maintained by mechanically regulating the turn ratio in the transformer winding, which can be achieved through OLTC or DETC. Since the tap changer is the only moving component of the transformer, it is particularly vulnerable to degradation mechanism. Many diagnosis tools have been developed to evaluate the mechanical integrity of tap contacts since many years ago. However, studies related tap changer diagnosis using FRA is still lacking. This thesis adapts, frequency response analysis which is proven to be a powerful and globally popular diagnostic tool in detecting power transformer mechanical integrity. Since this method is comparative, thus interpretation of FRA signal is still challenge and required skilled personnel to identify the cause of Fault. Two common tap changer deformation mechanisms and four types of transformer based connection test types are established. A lumped transformer model has been developed to identify the underline causes of FRA response curve changes between faulty and normal conditions for better interpretation. This model mainly focusses on low and mid frequency regions due to fact, that major changes occurs at the above-mentioned regions. In addition to that, this new technique of OLTC diagnosis will be recommended for future detection of tap changers faults and diagnosis of winding degradations simultaneously since they are interconnected by using the same instrument.
Alat ubah kuasa pengagihan elektrik beroperasi pada sistem penghantaran dan pengagihan yang memerlukan tahap voltan yang berbeza. Tahap potensi grid yang mencukupi dan berterusan dikekalkan dengan mengawal nisbah putaran penggulungan di dalam alat ubah secara mekanikal iaitu dapat dilaksanakan melalui OLTC atau DETC. Memandangkan pengubah tap adalah satu-satunya komponen alat ubah yang boleh digerakkan, secara khususnya ia sangat terdedah kepada mekanisma degradasi. Banyak alat diagnosis telah dicipta sejak beberapa tahun lalu untuk menilai keutuhan mekanikal sambungan tap. Walaubagaimanapun, kajian berkaitan diagnosis pengubah tap menggunakan analisis tindakbalas frekuensi (FRA) masih lagi kurang. Tesis ini menggunakan analisis tindak balas frekuensi (FRA) kerana ia telah terbukti menjadi sebuah alat diagnostik yang hebat dan terkenal di seluruh dunia dalam mengesan keutuhan mekanikal pada sesebuah alat ubah kuasa. Memandangkan kaedah ini adalah suatu bentuk perbandingan, maka tafsiran isyarat FRA adalah satu cabaran dan memerlukan sesorang yang mempunyai kemahiran untuk mengenalpasti punca kerosakan. Dua mekanisma ubah bentuk pengubah tap biasa dan empat jenis ujian sambungan asas alat ubah ditubuhkan. Sebuah model alat ubah telah dibangunkan untuk mengenalpasti punca-punca perubahan lengkungan tindak balas FRA diantara keadaan rosak dengan keadaan normal untuk penafsiran yang lebih baik. Model ini khususnya fokus pada bahagian frekunensi yang rendah dan serdehana kerana fakta menyatakan bahawa perubahan yang besar berlaku pada bahagian frekuensi seperti yang dinyatakan. Sebagai tambahan, kaedah diagnosis OLTC yang baru ini akan disyorkan pada masa akan datang untuk kegunaan mengesan kerosakan pengubah tap dan mengesan degradasi penggulungan secara serentak memandangkan kedua-duanya saling bersambung antara satu sama lain menggunakan alat yang sama.
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<tr>
<td>3D</td>
<td>3 Dimensional</td>
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<tr>
<td>HF</td>
<td>High Frequency</td>
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<tr>
<td>LV</td>
<td>Low Frequency</td>
</tr>
<tr>
<td>FB</td>
<td>Frequency Band</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
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<tr>
<td>KHz</td>
<td>Kilohertz</td>
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<tr>
<td>db</td>
<td>Decibel</td>
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<tr>
<td>cm</td>
<td>Centimetres</td>
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<tr>
<td>d</td>
<td>Depth</td>
</tr>
<tr>
<td>h</td>
<td>Height</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
<tr>
<td>Ω</td>
<td>Ohm</td>
</tr>
<tr>
<td>εᵣ</td>
<td>Dielectric constant / permittivity</td>
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<tr>
<td>σ</td>
<td>Conductivity</td>
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<tr>
<td>f₀</td>
<td>Resonant Frequency</td>
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<tr>
<td>V</td>
<td>Voltage</td>
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<tr>
<td>I</td>
<td>Current</td>
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<tr>
<td>R</td>
<td>Resistance</td>
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<tr>
<td>C</td>
<td>Capacitance</td>
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<tr>
<td>L</td>
<td>Inductance</td>
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<tr>
<td>G</td>
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<tr>
<td>Cu</td>
<td>Copper</td>
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<tr>
<td>S</td>
<td>Sulphur</td>
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CHAPTER 1

INTRODUCTION

1.1 Project Background

A transformer is a static device with complex geometrical electric network that used in electric power systems to transfer power between different circuits through the use of electromagnetic induction between winding, or two or more coupled windings, with or without a magnetic core [1]. The design and construction of a transformer depends upon the required power for the applications with the emphasis toward custom design especially for large unit which are used for step-up operation, primarily used at the generator and for step-down operation, mainly used to feed distribution circuits. This electrical apparatus is available as single-phase or three-phase arrangements. In addition to that, it is divided into types based on location namely; indoor and outdoor transformers. The former made of the dry type but can also be liquid immersed. However, the latter are usually liquid immersed [2].

Since the system required voltage may not match the transformer’s rated voltage, it is necessary to raise or lower the output voltage to supply nominal voltage to the load. In this case, a portion of a winding can be subtracted or added to control the winding turns ratio which is often desirable to compensate for variations in voltage level that occur due to the regulation of the transformer and loading cycles. This task can be accomplished by several means. However, there is a significant difference
between a transformer that can change the ratio while the unit is on-line (on load tap changer (OLTC)) [3] and one that must be taken off-line, or de-energized, to perform a tap change (de-energized tap changer (DETC)).

An on-load tap-changer (OLTC) is an electromechanical device, installed in a power transformer to regulate dynamic adjustment of load voltage to specified levels without interrupting load current. This device is crucial and expensive component of every power transformer [3][4]. The operation of voltage level control is achieved by changing the ratio of the transformer through connections of different numbers of turns in one of the transformer windings. This can be done through switches which are made by a moving contact connected to fixed taps of the transformer winding, so that the current has to go through the OLTC continuously during the switching operation. The range of operation frequency is from zero to several hundred thousand operations per year [3]. Thus, the OLTC contacts must withstand at least half a million operations as well as they must be able to remain in the same position for months or more without failure [3]. The contacts must work throughout the lifetime of the transformer, which is 25-40 years, since replacements are very expensive [5].

Therefore, it is necessary to ensure the healthiness and mechanical integrity of the OLTC during its life-time operation [5]. To guarantee this, analysts use various diagnostic methods that can be divided into oil and insulation analysis, analysis of tap changer contacts and mechanical analysis [6]. Each of this method of analysis involves several techniques of on load tap changer diagnosis techniques. However, these methods have their advantages and disadvantages. For instance, dissolved gas analysis (DGA) is by far the most common analysis technique which is achieved by taking an oil sample and extracts the gases which would result in identifying and quantifying the faulty tap changer using special laboratory equipment. However, this technique has a major disadvantage which cannot identify the exact location of critical faulty tap changer. Besides DGA, the dynamic resistance measurement (DRM) for checking the tap changer contact can be used by injecting a test voltage into the transformer winding using DC power supply. With a data acquisition card, the interface between the measurement unit and a control computer is created. Then a software is used to record the current pattern, show close-up graphs of the tap
changer operations, impedances and switching times for every tap position [7]. In addition to that, vibro-acoustic analysis which belongs to mechanical analysis is considered as a new technique that enables detection of various OLTC problems by analyzing the vibro-acoustic waveform which is transferred from the OLTC mechanism through the structural elements. The results obtained in one measurement are compared to the previously obtained reference results in order to detect the tap changer problems during its operation [6].

A recently innovative technique of on load tap changer diagnosis using frequency response analysis was developed even though information about it is lacking. This technique has examined the FRA sensitivity towards a faulty tap changer due to coking by using common end to end open and short circuit tests on the HV and LV winding [8]. Then, by simulating a faulty tap changer, the frequency response was able to show clear variations especially on the short circuit test [8].

Due to the lack of information involving this study, this research proposes to further investigate the sensitivity of transformer response towards the physical condition of tap changer through applying several faulty conditions of tap changer. Then, faulty tap changer will be simulated mechanically and the characteristic of the response due to faulty tap changer will be examined in order to determine the sufficiency of FRA measurements. It is expected that the response will have considerable difference between normal and simulated faulty tap changer. With the study on tap changer, the outcome could suggest that it is possible to use FRA for examining tap changer condition which will save time and cost as single measurement unit could monitor the transformer winding and the tap changer simultaneously.
1.2 Problem Statement

Electrical Power transformers operate on transmission and distribution systems which require different voltage levels. These large-scale transformers operating on electricity grids need to regulate the output voltage when the connected load change through changing the winding turns in order to maintain the output voltage within statutory limits. For instance, during daytime power demand increases which lead to decrease electric potential in electrical network. A sufficiently constant level of grid potential is maintained by mechanically regulating the turn ratio in the transformer winding, which can be achieved through an OLTC. Since the OLTC is the only moving component of the transformer it is particularly vulnerable. Approximately 40% to 56% of all transformer failures are caused by failures in the OLTC [9][10]. The reasons for these failures can be many and different failure modes are important under different operating conditions. This is often related to the older type of tap changers that are still in service as they are more prone to degradation mechanisms. These mechanisms are related to electrical, mechanical, thermal and chemical influences. Such failure modes contain mechanical wear of the contacts, excessive oxidation, coking, fretting and creep.

This expensive sub-component is considered as one of the most important parts of power transformer. Thus, malfunction or failure of OLTC can cause catastrophic measures of in-service power transformers. To reduce the unexpected failures of power transformers, proper and adequate maintenance on serviced aged OLTC must be done on a regular basis.

Detecting the transformer mechanical integrity is an important aspect that should be evaluated based on regular basis to ensure the physical healthiness of the transformer. For instance, a minor fault on load tap changer could allow the transformer to remain in operation, however may cause a destructive measure when later it develops into a total failure. This may be due to fault current and OLTC weak structure which is typically made of low resistivity and high corrosion resistance materials such as copper and aluminum. Therefore, knowing the condition of in-service aged OLTC is important to reduce the failure rate of power transformer.
Presently, several off-line and on-line diagnostic techniques have been used to diagnose the condition of load tap changer. These diagnostic results are important to determine the required maintenance on OLTC even though, strategic maintenances used for OLTC is based on the number of operations or yearly operating calendar [11]. For instance, FRA is one of the modern off-line diagnostic methods used to assess the condition of OLTC, though the existing studies which discuss the relationship between tap changer and FRA sensitivity is lacking. It is expected that this technique is able to find defects of OLTC parts which are not accessible for inspection and of benefits to maintain the reliability and availability of OLTC, thus power transformer as well.

To contribute to the improvement of FRA interpretation scheme, this thesis investigates the sensitivity of FRA measurement on several common tap changer deformations and explores a new potential diagnostic scheme of FRA that could be successfully implemented on OLTC diagnosis and detecting of problems associated with the contact wear and early stage of contact degradation in OLTC. In addition to that, this new technique will help to determine if there is any possibility to use FRA for monitoring the tap changer condition instead of just for monitoring the winding. Moreover, by understanding how the tap changer influences the frequency response, better analysis can be performed since one could differentiate between faulty or normal condition of tap changer. In addition to that, this new technique of OLTC diagnosis will be recommended for future detection of tap changers faults and diagnosis of winding degradations simultaneously since they are interconnected by using the same instrument.
1.3 Thesis objectives

In this thesis, the overall goal is to improve the understanding and interpretation scheme of frequency response analysis for assessing the condition of power transformers tap changer. In order to achieve this, the following objectives are listed:

i. Examines the characteristics of the frequency response due to various tap changer setting and deformation.
ii. Determine suitable electrical model for simulating the frequency response of a transformer tap changer.
iii. Simulate various tap changer setting and failure modes at low and mid frequency regions.
iv. Verify the simulation results by comparing with the actual frequency response measured from a transformer.

1.4 Thesis Scope

In this thesis, the overall scopes are to provide a clear idea on how the simulation and practical scheme of frequency response analysis will be applied for assessing the condition of power transformers tap changer. In order to achieve this, the following scopes are listed below:

i. Development of a suitable mathematical or electrical model for simulating the frequency response of a transformer tap changer which will be conducted using Solid work, Ansys Maxwell and MATLAB. The selected model supposed to be able to simulate various tap changer setting and failure modes.
ii. For this experimental work, the applied frequency will be varied between 20Hz to 2MHz, to analyze the major changes of tap changer deformation verses applied frequency.
iii. A leading Malaysian Electrical Company, namely TNB Research Sdn. Bhd (TNBR) will provide the required equipment for conducting the experimental work of this study. This experiment will involve basically, transformer rated with 300kVA, frequency response analyzer (FRA) and some other electrical and chemical equipment.

iv. Investigation, analysis and interpretation of the obtained output results will be showed clearly to give a comprehensive idea of this new techniques of on load tap changer diagnosis using various deformation techniques namely; coking, mechanical wear of the contacts, excessive oxidation, pitting corrosion.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Power Transformer

A transformer as a static, passive electrical device, consist of a complex network that contains of inductive, resistive and capacitive elements, used transfer power between circuits using electromagnetic induction. The term power typically refers to transformer used between the generator and the distribution circuits, which usually rated at 500 kVA and above [12]. This electrical apparatus and its main component is listed as shown on Figure 2.1.

Figure 2.1: Transformer Main Parts
2.2 Tap Changer

There are two types of tap changers used for winding turn ration control in order to maintain the voltage with nominal values namely; OLTC and DETC.-load tap-changers (OLTCs) are indispensable in regulating power transformers used in electrical energy networks and industrial applications [13]. The on-load tap changer (OLTC) adds the possibility to regulate the output voltage of a power transformer by changing the turn ratio whilst the transformer is under load. The large currents and voltages under which the transformer operates impose great demands on the contacts of the OLTC. This can be achieved in many ways, using different types of OLTC.

In addition to that, De-energized tap changer only be carried out when the transformer is not energized. Off-circuit tap changers are usually relatively simple switches mounted close to the winding tapings. The switches are under oil and are designed to change position only when the transformer is de-energized. There is consequently no breaking of current flow. The tap changer is operated by a handle, or wheel, from the outside of the tank in most transformers. This type of OLTC will is used in this project.

2.3 OLTC Types

There are two different types of OLTC namely; a diverter switch and a selector switch. The main difference between these designs is that a diverter switch type OLTC uses a tap selector to pre-select taps without switching current, in combination with a diverter switch to switch the load from the selected to the pre-selected tap. A selector switch type OLTC combines the selection of fine tap windings with the switching of the load current. To expand the regulating range of the arcing switch, the design can be extended by a change-over selector. The change-over selector can be implemented as a reversing change-over selector, a coarse change-over selector or a combination of both. Another difference in design principles is the transition
impedance that is used to control the circulating current that exists when two taps are selected during the transfer of the load current from one tap to another. These types of OLTC is illustrated as shown on Figure 2.2 and 2.3.

Figure 2.2: selector switch (arcing tap switch) [14]

Figure 2.3: Diverter Switch (Arcing Switch) with Tap Selector [14]
2.3.1 Load Tap Changer (LTC) Position Control

Through this project, the tap positions will be recorded in accordance with the test report for each test. For the transformer winding through this project will be assumed to be in a good condition. Bushings will not be under test, including neutrals, which should be disconnected from ground, unless grounding is required under FRA instrument guidelines which are recommended for certain tests only. In this test OLTC will be controlled manually and the test will be conducted each tap position. Figure 2.4 represent how OLTC position control will be accomplished. In this project, 5 positions tap changer will be used, the conducted experiment will be established in all position.

![Figure 2.4: OLTC Position Control and Its Mechanism](image)

2.4 OLTC Degradations Mechanisms

On-Load Tap Changers (OLTCs) are one of the problematic components of power transformers. Detecting faults in OLTCs is one of the key challenges faced by the power equipment predictive maintenance community. Most of the faults on power
Circuit Breakers (CBs) and On-Load Tap Changers (OLTCs) on high voltage transformers are of mechanical origin. Mechanical malfunction, mechanical wear and other types of abnormal behaviors can be detected as changes in the acoustic signatures [15]. Nowadays, several off-line and on-line diagnostic techniques have been used to diagnose the condition of load tap changer. These diagnostic results are important to determine the required maintenance on OLTC [11].

2.4.1 Oxidation

Temperature, water and oxygen are the main agents of oil insulation decomposition are a chemical phenomenon. The three mechanisms of degradation hydrolysis, pyrolysis and oxidation act simultaneously. Oxidation is the combination of the substance with oxygen [16]. However, this chemical reaction does not, require Oxygen at all time to occur as the name might imply, even though, its common. In most OLTC contacts design, most common materials are copper and silver. Two redox reactions with these materials, one including oxygen, the other not, are:

\[
\begin{align*}
2\text{Cu} + \text{O} & \rightarrow \text{Cu}_2\text{O} \\
2\text{Ag} + \text{S} & \rightarrow \text{Ag}_2\text{S}
\end{align*}
\]  (2.1, 2.2)

This chemical reaction of OLTC affects its conductivity because of Oxidation which gives arise to insulating or weakly conducting surface films on contacts which leads to high contacts resistance affecting operation of OLTC. In addition to that, the allowed impedances and losses according to IEEE standard C57.12.00 [17] allows a ±10% tolerance from the transformer loss specification. If the OLTC contacts are too heavily oxidized, they may contribute to the losses reaching these levels.
2.4.2 Coking

Coking is a process that occurs because of carbon extraction form the transformer oil to the OLTC contacts. This formation of pyrolytic carbon is called coking. Typically, this chemical Reaction happens when the contacts are overheated so that the activation energy is available to start the chemical reactions which the coking consists of.

The oil film, which consists of polymerized oil, reduces the conduction of the contact spot, thus leading to higher resistance. The higher resistance will in turn generate more heat which induces the formation of a thicker oil film layer. After this process, has been going on for some time the temperature has reached high enough values for the coking itself to start. This is when the temperature is close to 200 °C above the surrounding’s temperature [17]. The layer of carbon which is formed on the contact surface will now influence the contact in two ways. First, it will further reduce the conduction of the contact spot, leading to even higher contact resistance and more heat generation. Second, it will lower the thermal conduction away from the contact spot and will thus act as a heat insulator leading to complete contact failure [18]. This process can be illustrated as shown on Figure 2.5.

Figure 2.5: Left: An Original Stator Contact Block. Right: A Stator Contact Block with Heavy Pitting and Carbon, which Is Tested in The Test Model [18]
Mechanical wear occurs when two touching surfaces are in a relative motion, shearing forces develop leading to surface deformation, friction, mechanical wear, and so on, all of which are affected by surface topography, physical and chemical properties of the materials, the environmental conditions, and other factors [19]. Furthermore, mechanical wear can be classified in the following two types: In the first type, abrasive wear, this is produced when asperities and particles attached to one contact member cut into the other member and form grooves. The contact surfaces become very rough when abrasive wear takes place, and this makes it more probable that adhesive wear will take place, or even interlocking of the two contacts [9]. In the second type, adhesive wear, the two contact surfaces are dropped off by shearing or rupturing the adhesive contacts which can be illustrated as shown on Figure 2.6.

![Contact Surface Model](image)

Figure 2.6: Contact Surface Model [19]
2.4.4 Pitting Corrosion

Pitting corrosion is defined as a localized corrosion by which cavities or "holes" are formed in metals such as copper, however it can also occur for human body. This type of corrosion is considered more dangers than uniform corrosion damage because it is more difficult to detect, predict and design against. In addition to that pits are formed in hemispherical or cup-shaped. Typically, pitting in the advance aging stage, on the change-over selector contacts even though they switch under no-load condition. A high temperature, high load current and long term idle position of change-over selector are the source of this continuation process. The occurrence of pitting takes place not only on the rotor contacts (rollers) but also on the stator contacts [20]. At the advanced stage of pitting, the contact pitting looks like as shown on Figure 2.7.

![Figure 2.7: Extreme pitting on the stator contact surface [20]](image)

2.4.5 Fretting

Fretting is defined as the “accelerated surface damage occurring at the interface of contacting materials subjected to small oscillatory movements” [19]. However, information about this mechanism is lacking due to the many complex phenomena which can lead to fretting, and the many reaction trajectories which can give rise to
essentially the same damage. However, there are some characteristics that influence degradation mechanism such as contact design and condition, as well as the environment in which the contact operates. In addition to that, it was found that the effect of fretting on copper only give difference in micro ohm, since the influence of fretting on tap changer contact is very small and can be considered negligible.

2.5 Tap Changer Diagnosis Techniques

There are two types of transformer tap changers: an on-load tap changer (OLTC) and a de-energized tap changer (DETC). However, the latter only is used to conduct this experimental work.

On load tap changer is one of the most problematic components in power transformer since it is the only moveable part in power transformer. Previous studies on power transformer damage indicated that about 41 percent of transformer failures were due to on-load tap changers (OLTC) and about 19 percent were due to the windings [21]. In addition to that, the failure origins were 53 percent mechanical and 31 percent dielectric.

In addition to that, the type de-energized tap changer (DETC) is a versatile tap-changing switch, which is mounted inside the main transformer compartment attached to the cleat and lead structure of the transformer which cannot be moved while the transformer is energized. It often has 5 positions (A, B, C, D, E, or 1, 2, 3, 4, 5). Due to this, many research studies over the past decades developed many diagnostics techniques classified between online and offline to assess the physical condition and mechanical integrity of OLTC, so that could prevent catastrophic failure to power transformer. This monitoring technique entails the continuous checking of parameters that can be acquired on-line or offline which can generate alarms directly when a defect arises. Most of OLTC diagnostic techniques
2.6 Sweep Frequency Response Analysis (SFRA)

Frequency response analysis is a powerful, sensitive, and non-destructive diagnostic test for detecting and evaluating changes in the electrical characteristics of windings, tap changers, clamping structure within power transformer by measuring their electrical transfer functions over a wide frequency range [22]. Such changes can result from various types of electrical or mechanical stresses (shipping damage, seismic forces, loss of clamping pressure, short circuit forces, and insulation failure). Some of these deformation mechanisms are illustrated as shown on Figure 2.9. Basically, this comparative method is achieved through comparing an actual set of SFRA results to reference results. However, it is relatively new to power industry with drawbacks such as difficulty of interpretation of the test result, but it offers a valuable opportunity to improve the reliability of transformers, to reduce maintenance costs and, most of all, to avoid expensive unexpected outage or catastrophic failures of power transformers.

2.6.1 Assessment of Measured Traces of SFRA Test [23]:

Basically, FRA is a comparative method which implies that any sort of reference data must be available to analyze the test results. Three methods are commonly used to assess the measured traces:

i. Time-Based: current SFRA results are compared to earlier measurement of the same transformer.

ii. Type-Based: SFRA of one transformer are compared to another identical unit (sister unit).

iii. Phase Comparison: Current SFRA results of one phase are compared to the results of the other phases of the same transformer under test.
2.6.2 Typical Applications of SFRA Measurements [23]:

1. Transformer check after short circuit testing.
2. Integrity verification of transformers after transportation and mechanical shocks e.g. (earthquake).
3. Condition assessment after the occurrence of high transient fault currents.
4. Routine diagnostic measurement.
5. Diagnosis after transformer alarm or protection tripping.
6. Testing after significant changes of monitored values (e.g. combustible gases).
7. Further inspection after the observation of unusual routine test results.
8. Scientific investigations.
9. LTC and DETC mechanical integrity as well the position of OLTC can affect the entire frequency range relevant for the assessment. When adding, or removing turns it will not just affect the copper losses, leakage inductances, parasitic capacitances of the individual turns, but also the magnetizing inductance and parasitic capacitance coupled with the iron core. This explains why the response changes over the entire frequency range rather than just a portion of the range. High contact resistance readings can be detected by FRA testing[24]. Any metal to metal mating surface that connects the bushings to the windings, LTC or DETC can lead to higher impedances through the test circuit applied. The result can cause changes in both the low and highest frequencies. Poor contact resistance can be caused by connections that have worked themselves loose, corrosion, contact build-up or burning [8][24][25][26][27][28].
Figure 2.8: Transformer Defects. (a) Deformed Core, (b) Collapsed Tap Winding, (c) Damaged Main Winding and (d) Displaced Internal Connection
2.6.3  Principle of Operation

A transformer is a complex circuit network which consist of resistance of the winding, capacitance of insulation layers between coils, winding, winding and core, core and tank, and tank and winding [29]. The internal geometrical parameters of the transformer generate a unique signature when variable frequency signals are injected at discrete frequencies. The responses is plotted in terms of phase and magnitude[26] as shown on Figure 2.9 Figure 2.10.

Figure 2.9: Transfer Function Measurement in Frequency Domain on a Power Transformer

Figure 2.10: SFRA Principle of Operation (left) and simplified Geometrical model of transformer’s active part (right)
In this method, the magnitude and phase shift measurements are taken at predefined frequency points by applying constant amplitude sinusoidal signals across the winding to derive the winding end-to-end frequency response in the form of magnitude against frequency as for the commonly used admittance is illustrated in Figure 2.11 with the derived equation 2.3. In this method, the source signal can be held at constant amplitude for a specific length of time, input digitizer of the instrument has enough time to adjust gain setting resulting in a better dynamic performance.

\[ H(f_n) = \frac{Y(f_n)}{X(f_n)} \]

Figure 2.11: Determination of Frequency Response by Frequency Sweep Method

\[ H(f_n) = 20 \text{Log}_{10}\left(\frac{Y(f_n)}{X(f_n)}\right) \text{ dB} \quad 2.3 \]

Hence the measured frequency response is plotted graphically by plotting the logarithmic amplitude ratio of the output voltage to the input voltage in dB versus frequency response on y-axis and x-axis respectively. For better and clear frequency range, logarithmic is preferable however linear is better for discrete frequency bands and do compare small difference at certain frequencies. Figure 2.12 and Figure 2.13 illustrate a typical repose of LV winding using logarithmic and linear respectively.
Figure 2.12: Logarithmic scale of Frequency Response [24]

Figure 2.13: Linear scale of Frequency Response [24]
2.6.4 Frequency Response Analysis for DETC and LTC Contact Resistance Diagnosis

Though not necessarily a classical failure mode, high contact resistance readings can be detected by FRA testing. Any metal to metal mating surface that connects the bushings to the windings, LTC or DETC can lead to higher impedances through the test circuit applied. The result can cause changes in both the low and highest frequencies. Poor contact resistance can be caused by connections that have worked themselves loose, corrosion, contact build-up or burning. Typical graphs of frequency response are illustrated as shown on Figure 2.14 and Figure 2.15.

Table 2.1: Contact Resistance Frequency Region [24]

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Contact Resistance Assuming No Other Failure Mode Exists</th>
</tr>
</thead>
</table>
| 20 Hz to 10 kHz | Open Circuit Tests:  
This region (core region) is generally unaffected by the presence of contact resistance. |
| 5 kHz to 100 kHz | Short Circuit Tests:  
The results will not compare well against previous data or amongst phases. The affected winding is generally offset |
| 50 KHz to 1 MHz | Open Circuit and Short Circuit Tests:  
This range can shift or produce new resonance peaks and valleys. The changes will be greater for the affected phase. |
| > 1 MHz | Open Circuit and Short Circuit Tests:  
This range can shift or produce new resonance peaks and valleys. The changes will be greater for the affected phase. |
Figure 2.14: Contact Resistance Response form LV Open Circuit Test [24]

Figure 2.15: Contact Resistance Response form HV Short Circuit Test [24]
REFERENCES


