INVESTIGATING INTER-TURN FAULT IN TRANSFORMER
USING TTR AND FRA

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DEDICATION

This study is wholeheartedly dedicated to my beloved parents (**Mr. SALMAN)** may Allah have mercy on his soul and **(Mrs. AMAL**), who have been my source of inspiration and gave me strength when I thought of giving up, who continually provide their moral, spiritual, emotional, and financial support. To my brother (**Mr. AQEEL**), who shared their words of advice and encouragement to finish this study. Finally, to my beloved wife (**Mrs. HAWRAA**) and my beloved child(**RIDAH**).thank for all of you"

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How much I wished that my father, may Allah have mercy on his soul, was with me to see that I have accomplished his and my dream by obtaining the Master's degree. Here I would like to dedicate my success to him and thank him.

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For my darling wife, a very special thanks for trusting me and being very patient during my absence in Malaysia. And finally I again thank Allah for the presence of his great gift, my beloved son **RIDHA**.

ABSTRACT

Transformers are one of the significant elements in the power system network. The Transformer function is to step up and down the voltages. When the transformer operating in high load, it exposes to failures. There are various transformer failures which could have a serious effect on the transformer efficiency. For example, winding deformation, tap changer damage, and short turns (inter-turn fault). The transformer inter-turns fault reduces the number of turns in the winding. To detect inter-turn fault, the transformer turn ratio test is the basic method used. On the other hand, frequency response analysis has been recognized to monitor the mechanical condition of the transformer winding. The frequency response analysis method can be conducted in four measurement connection. They are end to end open circuit test, end to end short circuit test, capacitive inter-winding, and inductive inter-winding. The inductive inter-winding low-frequency region is determined by the transformer turn ratio. This statement was mentioned in CIGRE A2.26. However, there are not approved studies on this issue. This study investigates the transformer inter-turn fault using transformer turn ratio test and frequency response analysis. In addition, this study performs various of statistical indicators on the FRA results. The statistical indicators are used to detect the variation between the normal and inter-turn fault responses. Also, this study proposes statistical indicators limits. After that compare the FRA and TTR results and check if the turn ratio results can be obtained using FRA inductive inter-winding test. Findings that FRA inductive inter-winding test can detect inter-turn fault. This can be determined by the absolute sum logarithmic error (ASLE), mean square error (MSE), and standard deviation (SD). Also, there are indicator limits has been proposed for ALSE and SD. This study finding helps to use the frequency response analysis method to replace the conventional turn ratio test.

ABSTRAK

Transformer adalah salah satu unsur penting dalam rangkaian sistem kuasa. Fungsi Transformer adalah untuk meningkat dan menurunkan voltan. Apabila pengubah beroperasi dalam beban tinggi, ia akan terdedah kepada kerosakan. Terdapat pelbagai kegagalan transformer yang boleh memberi kesan yang serius kepada kecekapan pengubah. Sebagai contoh, ubah bentuk penggulungan, kerosakan changer paip, dan giliran pendek (kesalahan bergilir-gilir). Kesalahan antara pengubah transformer mengurangkan bilangan lilitan dalam penggulungan. Untuk mengesan kesalahan antara giliran, ujian nisbah pusing transformer adalah kaedah asas yang digunakan. Sebaliknya, analisis tindak balas frekuensi telah diiktiraf untuk memantau keadaan mekanikal penggulungan pengubah. Kaedah analisis tindak balas frekuensi boleh dilakukan dalam empat sambungan pengukuran. Mereka berakhir untuk mengakhiri ujian litar terbuka, mengakhiri ujian litar pintas, kapasitif inter-penggulungan, dan induktif antara penggulungan. Rintangan frekuensi rendah induksi antara induktif ditentukan oleh nisbah putar pengubah. Kenyataan ini disebut dalam CIGRE A2.26. Walau bagaimanapun, tidak ada kajian yang diluluskan mengenai isu ini. Kajian ini menyiasat kesalahan transformer antara giliran menggunakan ujian nisbah putar pengubah dan analisis tindak balas frekuensi. Di samping itu, kajian ini memaparkan pelbagai petunjuk statistik mengenai keputusan FRA. Petunjuk statistik digunakan untuk mengesan variasi antara tindak balas kesalahan biasa dan antara giliran. Selepas itu bandingkan hasil FRA dan TTR dan periksa apakah keputusan nisbah putaran boleh diperolehi dengan menggunakan ujian antara penggulungan FRA induktif. Penemuan bahawa ujian antara penggulungan FRA induktif boleh mengesan kesalahan antara giliran. Ini boleh ditentukan oleh kesilapan logaritmik mutlak (ASLE), ralat kesilapan persegi (MSE), dan sisihan piawai (SD). Penemuan kajian ini membantu menggunakan kaedah analisis tindak balas frekuensi untuk menggantikan ujian nisbah pusingan konvensional.

Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

FRA	-	Frequency Response Analysis
SFRA	-	Sweep Frequency Response Analysis
TTR	-	Transformer Turn Ratio
CC	-	Correlation Coefficient
ASLE	-	Absolute Sum Logarithmic Error
DABS	-	Absolute Difference
MSE	-	Mean Square Error
SD	-	Standard Deviation
MM	-	Maximum Minimum
FDS	-	Frequency Dielectric Spectroscopy
DR	-	Dynamic Resistance
C_s	-	Series Capacitance
R_s	-	Series Resistance
L_s	-	Series Inductance
C_g	-	Capacitance to the Ground
TF	-	Transfer Function
TRF	-	Turn Ratio Finder
OLTC	-	On-Lode Tap Changer
dB	-	Decibel (logarithmic scale)
ρ	-	Resistivity of copper
A	-	cross-sectional area of the specimen
l	-	Length of the specimen
R	-	electrical resistance of a uniform specimen of the material

CHAPTER 1

INTRODUCTION

1.1 Background study

A transformer is the most expensive single part equipment in electric power transmission network and rated in kilovolt-ampere (kVA). Transformer main function is to step-up and step-down the voltages. The transformer design depends on its applications. There are single-phase and three-phase transformers. In addition, they are divided into two types based on location, such as indoor and outdoor transformers. On the other hand, it is classified into dray (cast resin transformers) and oil transformers [1]. Fundamentally, transformer targeted to deliver safe and reliable electricity to the customers and the public. Due to high development in constructions increasing the need for electricity. So, operating in high loading to meet demands transformers exposes to failures. In addition, there are other external effects might cause transformer damages such as transportation, earthquakes, oil combustion and short circuit [2].

Transformers failures could occur at any part. Based on a study conducted on new trends of transformers in [3] it is mentioned that about 40% of transformer damage found in OLTC and 30% in the winding. These are the highest percentages where transformer failures can be found. Other failures percentages are shown in Figure 1. 1. Online and offline diagnosis monitoring of transformers is required to detect the fault at an early stage. This monitoring at an early stage of fault can prevent degeneration of power which might be a catastrophic phenomenon.

It is well known that when a transformer relocated or at the end of manufacture stage required to verify that the transformer is clear or no damage. There is a multitude of test performed to the transformer by specialists during assembly, while other tests performed on the installed location. There is some conventional and improved test which can be performed in order to detect transformer failures [4]. The following list is the common tests to monitor transformer condition:

- Winding resistance measurement
- Insulation resistance measurement
- Dielectric dissipation factor/ tan delta
- Frequency dielectric spectroscopy (FDS)
- Dynamic winding resistance measurement (DRM)
- Leakage reactance measurement
- Transformer Turn ratio measurement (TTR)
- Frequency response analysis (FRA)

Transformer Turn ratio (TTR) measurement method compares the transformer ratio with the standard adjusted ratio. TR test can be performed when the transformer is installed or after relocated. It is a well-known method for transformer winding monitoring. However, Frequency response analysis (FRA) is widely used as a modern method to investigate the transformer condition. It is stated in CIGRE [5] that FRA used to assess the mechanical condition of the transformer winding. Also, in IEEE [6] standard and IEC 60076-18 mentioned that FRA can be used to investigate the mechanical condition of the transformer. However, FRA has become a powerful and sensitive method to investigate mechanical and non-mechanical damage within the transformer. An example of non-mechanical damage is insulation degradation. To investigate transformer condition, basically might be valuable to perform turn ratio measurement and FRA measurement. On the other hand, there are various of statistical indicators used to calculate the variation between the normal and fault responses. For example, there are correlation coefficient (CC), Absolute Sum Square Logarithmic Error (ASLE).

This research proposes to investigate the winding inter-turn fault using transformer turn ratio test (TTR) and FRA. The two methods are communally used in transformer monitoring. However, the transformer turn ratio test is spatially used for winding. FRA also investigate the mechanical condition of the transformer winding.

In this research, two transformers will be investigated. First, perform FRA test on all tap settings, perform TTR test on all tap settings, compare result between FRA and turn ratio test. In the comparison, it is needed to realize if it can obtain a result on turn ratio from turn ratio test using FRA. If can, then there is no need to do turn ratio test, FRA will be enough to provide information on the turn ratio. Then, repeat the measurement on the second transformer to verify the results. Lastly, performer inter-turn fault on the turns ratio, then conduct FRA inductive inter-winding test and compare the turn ratio results and FRA results.

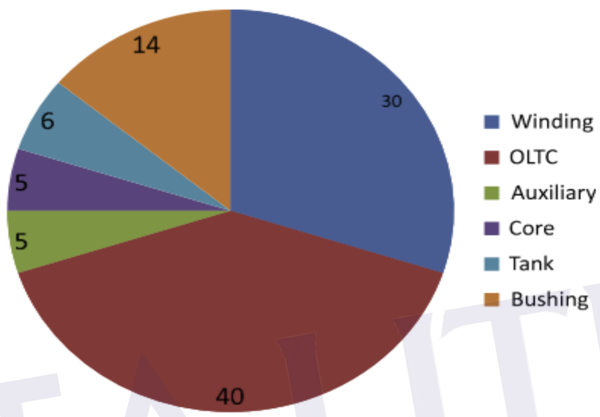


Figure 1. 1: Transformer failures and its percentage based on CIGRE international survey[3]

1.2 Problem statement

The FRA method was recognized to be used for power transformer winding damage detection. Nowadays, FRA widely used to investigate non-mechanical damages such as winding insulation degradation. However, there still some methods used to investigate transformer winding such as transformer turn ratio test. On the other hand, there is a statement in CIGRE standard working group A2.26 [7] stated that in inductive inter-winding at low-frequency range is determined by the winding turns ratio. Basically, laboratory work on actual transformer can give more explanation on the ability to replace turn ratio test using the FRA inductive inter-winding. There are two types of inter-winding faults can alternate the winding ratio. They are inter-turn fault and inter-disc fault. In this research study, the inter-turn fault is used. This is because inter-turn fault can be performed by shorting the winding taps. However, inter-disc fault can be applied by creating damage between winding discs which is difficult and causes serious damage to the transformer. The FRA results analysed using statistical indicators. For the TTR test, the ratio between the measured and calculated results should not accede 0.5%. For statistical, there is not proposed limit to judge the results.

1.3 Objectives

i. To investigating transformer inter-turn fault using FRA inductive inter-winding test and transformer turn ratio (TTR).
ii. To use low-frequency region of FRA inductive inter-winding measurement to evaluate the conventional turn ratio test for detecting the changes in winding turn ratio.
iii. To propose new indicator limit based on FRA statistical analysis.

1.4 Scope of study

The project is executed in accordance with the followings:

a. The measurement conducted on TNB Research center, Bangi, Selangor.
b. Two units of Delta-wye connection Dyn11 three phase distribution transformers which located at TNBR. Transformer A is 150kVA and transformer B is 500kVA.
c. FRAnalyzer FRANEO 800 for FRA measurement.
d. Simulation data, plots figures in MATLAB to show clear frequency response scale and make figures insets.
e. Turn ratio test will be conducted on three phase transformer using commercial test equipment.
f. In the experimental work, the frequency range analyzed in between 20Hz to 2MHz.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to the transformer

Transformers are electrical devices, consist of a combination of the resistive, inductive and capacitive network. There are different transformer depends on the function. Large power transformer located at power generation and substation which usually rated at 500kVA. Distribution transformers are located on the street to distribute the power into houses. The main parts of the transformer are shown in Figure 2. 1 [8].

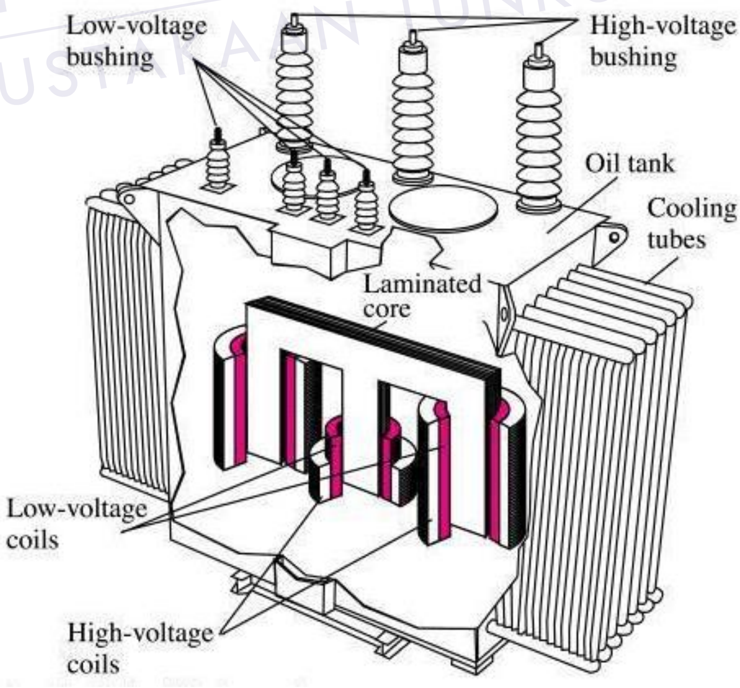


Figure 2. 1: Transformer main parts [9]

2.1.1 Transformer winding and core

Cores and winding are the active part on transformers. Core commonly used a small and thin iron or steel including the limbs. This is to reduce the eddy current losses [10]. The power transformer is a combination of RLC electrical components as shown in Figure 2. 2. There is a series inductance Ls, series capacitance Cs, resistance R, and capacitance to the ground Cg.

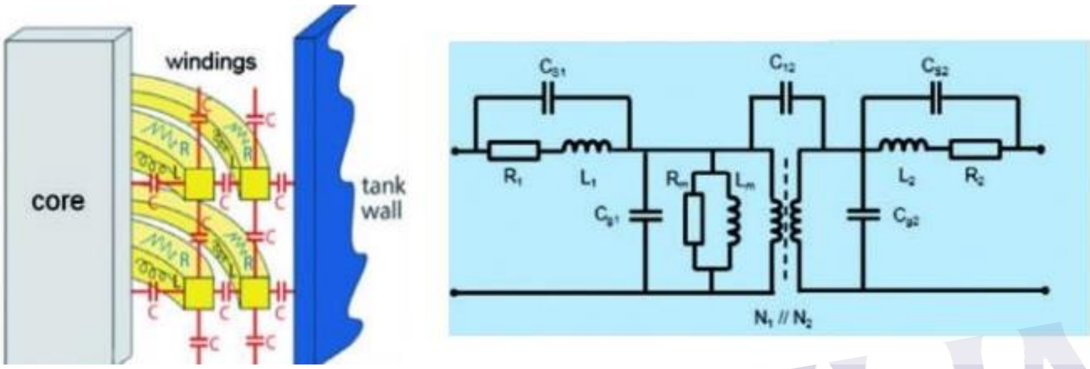


Figure 2. 2: Transformer winding core form of RLC circuit competition

2.2 Transformer inter-winding fault

There are two inter-winding faults which are inter-turn and inter-discs. The inter-turn fault of the transformer winding occurs when the isolation of two winding turns is degraded. Then the effective numbers of winding turns are decreases. The inter-disc fault is similar to inter-turns but, this fault occurs between two discs.

According to M. F. M. Yousof, C. Ekanayake, and T. K. Saha in [11], the inter-disc fault has been investigated using FRA. It is found that inter-disc fault commonly occurs at the top and bottom half of winding which is constantly exposed to a higher temperature. This finding from the almost identical responses obtained using FRA. other research works which investigate the inter-disc fault using FRA perspective are discussed in [12], [13]. The inter-disc fault is shown in Figure 2. 3.

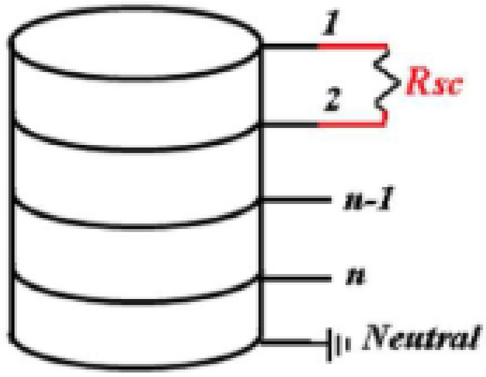


Figure 2. 3: Inter-disc fault between the first and second discs [14]

In this study the inter-turn fault has been investigated using FRA and TTR. The inter-turn fault can be simulated by adding small resistance *Rsc* between turns as shown in Figure 2. 4.

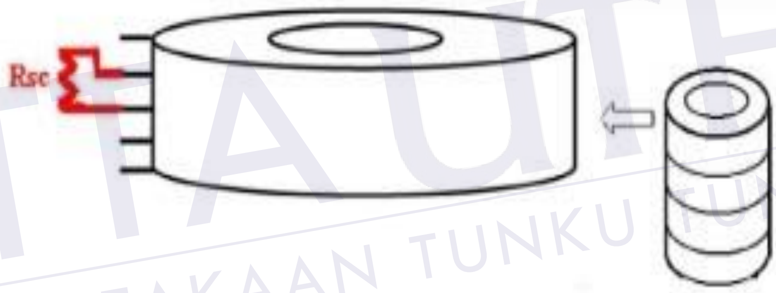


Figure 2. 4: The inter-turn fault shows in the second section in the circuit model equal to the short circuit in the second group in the first disc [14]

Jafar Nosratian Ahour et al in [15], investigated the inter-turn fault using FRA method. It is founded that, 10% of short turns cannot be detected using a conventional method such as dissolved gas analysis (DGA). Another study investigate inter-turn fault using FRA in [16]. It is concluded that FRA can indicates changes in the frequency response in the range 150 to 200 kHz. This study investigates the inter-turn fault by shorting the winding taps. The method followed to performer short turns is explained in chapter 3 section 3.3.3. Another study investigates the sensitivity of FRA to inter-turn fault by created a short circuit between two adjacent tums. The resonance frequencies are shifted and there is a large variation in the amplitude [17].

2.3 Introduction to frequency response analysis

Frequency Response Analysis (FRA) is known as a sensitive diagnostic method for detecting changes in the electrical characteristic of the transformer winding. This change is a resultant of electrical or mechanical stress which later shaping transformer failures. FRA measuring the impedance of inductive and capacitive elements within transformers. The measurement results over a wide range of frequencies. Then the measured results compared with the reference signature of the transformer to measure its condition [6].

2.3.1 FRA test configuration

The FRA describe the magnitude maximum or minimum appearing in the frequency response function. FRA measurement conducted by applying a small AC sine wave voltage in one terminal and measure the output signal at another end of the winding shown in Figure 2. 5. Then, the frequency response analysis transfer function *H(f)* in (2.1) consists of the magnitude and phase angle. The FRA magnitude is the amplitude of divided the input signal and the output signal as in (2.2). On the other hand, the FRA phase is the phase shifting of response relative to that of the input signal as in (2.3).

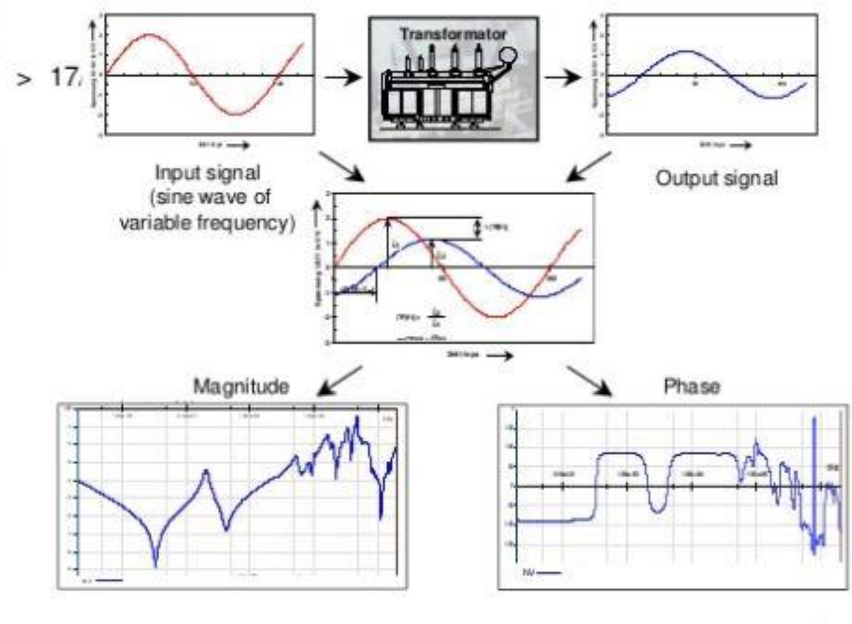


Figure 2. 5: The basic operation of the FRA

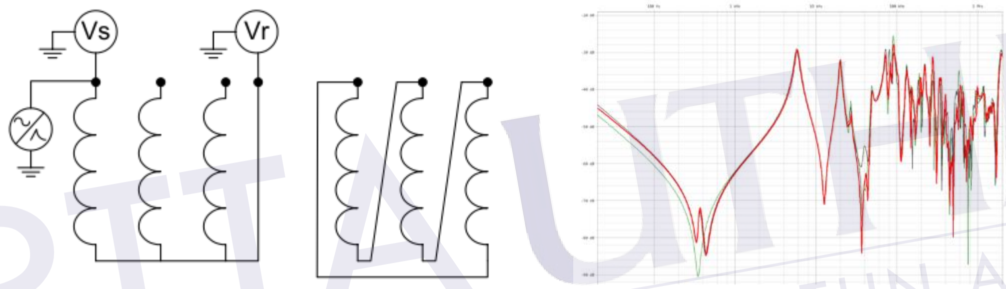
$$H(f) = \frac{U2(f)}{U1(f)} \tag{2.1}$$

$$K(f1) = 20log_{10}\frac{U_2(f)}{U_1(f)} \tag{2.2}$$

$$\emptyset(f1) = \ tan^{-1}\frac{\angle U_1(\mathrm{f})}{\angle U_2(\mathrm{f})} \tag{2.3}$$

a) End to end open circuit test:

Open circuit measurement, it is performed at one winding HV or LV. The input signal is injected into one terminal of winding and measured at the other end of the winding. The open circuit measurement test can be conducted to both single phase and three phase transformers. The open circuit is referring to the secondary winding all other terminals floating through measurement showed in Figure 2. 6 (a). The results will look like the frequency response in Figure 2. 6 (b).



a b

Figure 2. 6: End to end open circuit test (a) test connection (b) example of test results.

b) End to end short circuit test:

Short circuit measurement, it is similar to an open circuit but the difference in the secondary winding terminals are all connected together during measurement. For instance, one end of a high-voltage winding to another while the associated low voltage winding is shorted shown in Figure 2. 7 (a) and the results frequency response as shown in Figure 2. 7(b).

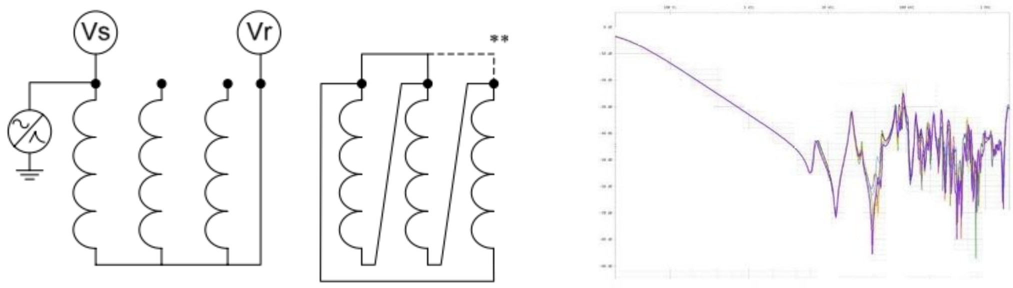


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Figure 2. 7: End to end short circuit test (a) test connection (b) example of test results.

c) Capacitive inter-winding test:

The capacitive inter winding also known as the inter-winding measurement and it is applied at two different windings. Capacitive inter windings are performed by applying the signal at one end of a winding and take the reading signal at an end of another winding and the others ends are open shown Figure 2. 8(a). Figure 2. 8(b) shows the measured response former this certain configuration.

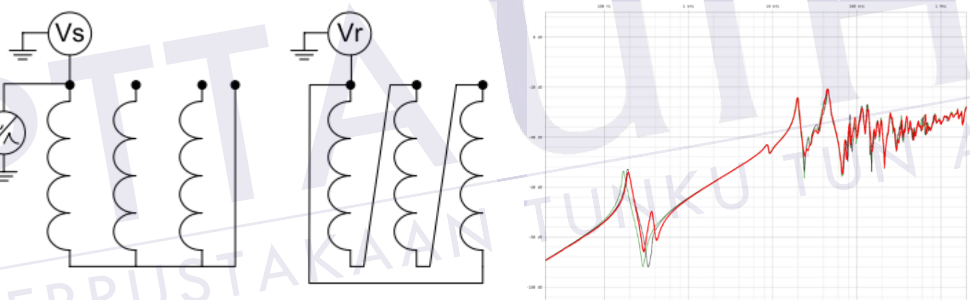

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Figure 2. 8: Capacitive inter-winding test (a) test connection (b) example of test results

d) Inductive inter-winding test

inductive inter windings measurement conducted by applying the signal at one end of the winding and taking the signal from any end of the other winding with one terminal grounded from each winding. The measurement configuration and output results are shown in Figure 2. 9(a, b).

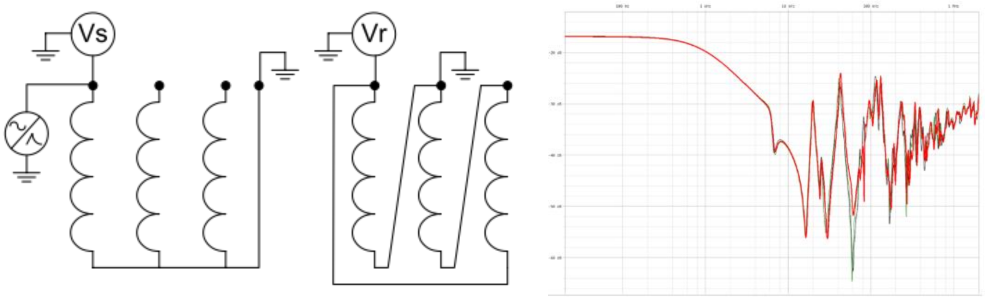

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Figure 2. 9: Inductive inter-winding test (a) test connection (b) example of test results

2.3.2 FRA sub-bands

The frequency response sub-bands are different from one transformer to another. It depends on the size of the transformer and other epacts such as design and arrangements. Based on IEEE standard [6], there are four sub-bands which refer to the low-frequency range, middle frequency range, high-frequency range and super-high-frequency range as shown in Figure 2. 10. In every sub-band, it is sensitive to a particular failure as shown in Table 2.1.

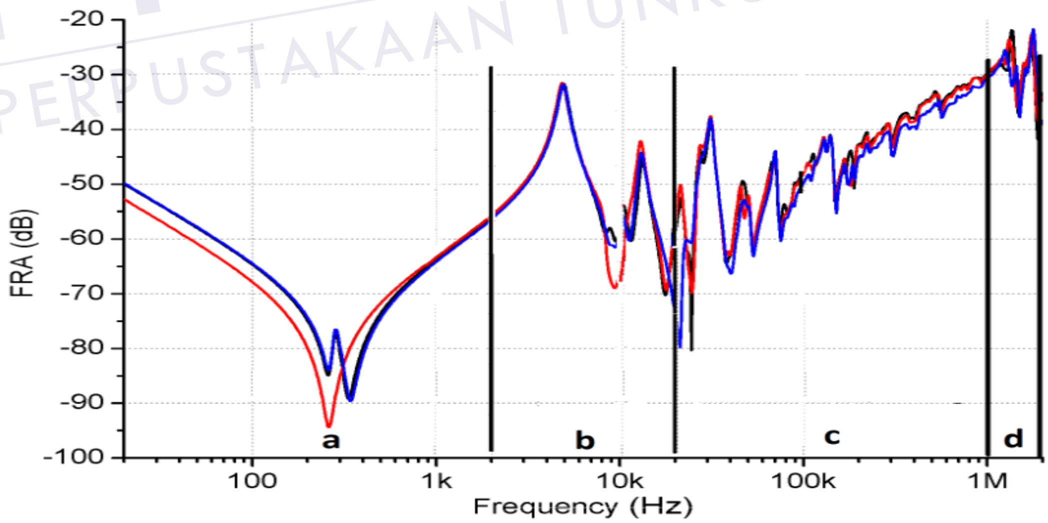

Figure 2. 10: Frequency response sub-bands based on IEEE standard

Table 2. 1: frequency response sub-bands and its sensitivity to failures [18].

Region	Frequency sub-band	Sensitivity to failure
a	<2kHz	Core deformation, open circuits, shorted turns and residual magnetism
b	2kHz to 20kHz	Bulk winding movement between windings and clamping structure
c	20kHz to 1MHz	Deformation within the main or tap windings
d	1MHz to 2Mhz	Movement of the main and tap windings, ground impedances variations

2.3.3 FRA interpretation

The sweep frequency response analysis (SFRA) is an analysis technique for detecting winding displacement and deformation (among other mechanical and electrical failures) on power and distribution transformers. Nowadays, there is an increasing interest in SFRA method because of its sensibility in detecting mechanical faults without opening the unit [19]. It involves a comparison between measured and reference data, and if any deviation is found, deterioration can be suspected. The comparison may be time-, design- or type-based [20]. What amount of deviation shall be suspected as an indication of damage or deformation? What variations in data shall be considered negligible or significant? A skilled judgment is needed to answer such questions. For inexperienced engineers, comparison on a numerical basis, if made available, is handy for the purpose [21]. Researchers have proposed many techniques to quantify deviations between SFRA signatures. Statistical techniques have been widely used for the purpose, Statistical factors [error functions, correlation coefficients (CC) etc.], when applied on several frequency sub-bands, can provide an objective measure of the differences between two SFRA graphs[20]. The advantages of using the proposed statistical indicators have been demonstrated through two case studies.

The CC (2.4) is defined as the potency of linear association between two data variables [22]. Its value varies from -1 to +1. If the CC value is +1, it means that the two sets of data have a strong correlation, whereas the '0' value suggests no linear association between them. Values between 1 and 0 indicate strong/weak association depending on their closeness to/distance from 1 (see (2.4)) This is a widely used statistical parameter for SFRA diagnostics. The limitation of this parameter is that it gives a wrong conclusion when X(i) = aY(i), where i = 1, N and a is a constant; its value becomes 1 in this case, even though there is a change in data [23], [24]. Although the relation X(i) = aY(i) will not be valid for the entire frequency band, it may be true for a small frequency band leading to a wrong diagnosis. Furthermore, there could be a question mark on the threshold value of the CC index. According to [25], a value of CC less than 0.9998 may be suspected for deviation of data, but in practice lower values are recorded even for healthy transformers.

$$CC_{(X,Y)} = \frac{\sum_{i=1}^{N} X(i)Y(i)}{\sqrt{\sum_{i=1}^{N}[X(i)]^2 \sum_{i=1}^{N}[Y(i)]^2}} \tag{2.4}$$

There are other statistical indicators can be summaries in the following:

Standard Deviation (SD):

This is a statistical parameter used in [25], [26] for a diagnostic Purpose. It has been termed as SD there. However, SD is generally defined as the square root of the sum of squares of deviations of one data set from its mean value [22]. SD indicates the variation of data from the mean value within a single data set. It is more appropriate to identify the parameter as RMSE when compared with MSE as given in (2), as N -1 ≌ N for a large number of sample points.

$$SD_{(X,Y)} = \sqrt{\frac{\sum_{i=1}^{N}[Y(i)-X(i)]^2}{N-1}} \tag{2.5}$$

Mean Square Error (MSE):

One of the inherent qualities of MSE is that it suppresses small errors and magnifies large errors. Ideally, that is when the two data sets are perfectly matching, its value is zero. A small difference (less than 1 unit) is shrunk and deviation more than 1 unit is magnified. Thus, the MSE parameter indicates the severity of difference between the two sets of data. A few researchers feel that MSE unnecessarily underestimates or overestimates the deviation, that is it is ill scaled [24].

$$MSE = \frac{\sum_{i=1}^{N}[Y(i)-X(i)]^2}{N} \tag{2.6}$$

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