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Interpretation of Inter-Turn Fault in Transformer Winding Using Turns Ratio Test and Frequency Response Analysis

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***Abstract*—The transformer is critical equipment in electrical power systems as it is continuously exposed to various failures. Inter-turns fault in the transformer reduces the turns of the winding, thus it can be detected using a Transformer-Turns-Ratio (TTR) test. On the other hand, the Frequency Response Analysis (FRA) method is used for assessing the mechanical condition of the transformer winding and core. In this paper, the TTR, and FRA methods are proposed to detect the inter-turns fault in the transformer winding. The winding inter-turn fault was investigated using FRA inductive inter-winding measurement and compared with the TTR test. Findings from the statistical analysis showed that FRA inductive inter-winding can detect the inter-turn fault. Finally, acceptance limits for the absolute sum of logarithmic error and standard deviation were proposed. The limits were established based on TTR's acceptance limit from the IEEE standard. This finding proves that the FRA test can be used to complement the result in the conventional TTR test.**

***Index Terms*—Frequency response analysis, inter-turn, power transformers, short circuit, transformer turns ratio**

I. INTRODUCTION

Power transformers are crucial components in the power system to adjust the voltage to suitable levels. In fact, it is considered the highest costly equipment in the electrical power transmission system. The reliability of the transformer is crucial to maintaining the power supply. The increasing electricity demand is forcing the existing transformers to operate under high loading conditions. This accelerates the ageing of the transformer insulation system, thereby further increasing the risk of failure. Other external elements might cause serious damage to the transformer such as short-circuit current fault, mishandling during transportation, and natural earthquakes [1], [2].

Failures could occur in any part of the transformer. Based on a study, it was mentioned that about 40% of transformer damages were due to on-load tap changers (OLTC) while 30% were at the main winding. These are the sites where transformer failures are most likely to be found. Fig. 1 introduces the percentages of power transformer failures occurring in different parts [3].

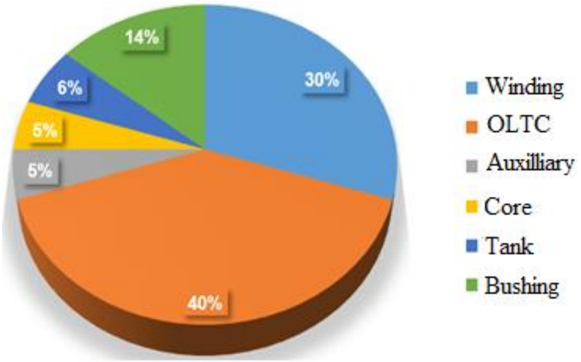

Fig. 1. Percentage of the transformer failure based on its parts according to CIGRE international survey [3].

The short circuit fault in transformer winding can be categorized as either the inter-turn fault or inter-disc fault. The inter-turn fault occurs when two or more turns in the same winding are shorted. The inter-disc fault occurs when two or more turns in different winding discs are shorted. Both faults reduce the effective number of turns. However, the latter is more significant in affecting the measured result. Nevertheless, the detection and diagnosis of these faults are difficult tasks [4].

The inter-disc fault has been studied using FRA in [5]. The fault was investigated by applying a short-circuit connection at the top and bottom half of the winding. However, it did not consider the inter-winding test configuration. Other research work that investigated the inter-disc fault using the FRA test were also presented in [6]. These two references also did not consider the inductive inter-winding test as part of the analysis. J. N. Ahour *et al*. in [7] presented an investigation on the inter-turn fault. There are 10% of shorted-turns failures that cannot be discovered by conventional measurement methods or tests. In [8], the authors study the inter-turns fault using FRA. The study concluded that the response at 150 Hz to 200 kHz indicated some variations. Another study was conducted to explore the ability of the FRA to

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detect the inter-turn fault [9]. The study measures the FRA for a shorted circuit winding between adjacent turns. It was concluded that the response shifted and there was a variation between responses magnitude (dB). In general, the references mentioned earlier have conducted investigation on the same winding failure but only considered end to end test configuration of FRA. The inductive inter-winding test configuration of FRA is currently lacking of investigation. Besides FRA, the TTR test can detect faulty winding, especially shorted turns. The TTR test has an acceptance limit of 0.5%, according to the international standard [10] and is one of the standard electrical test for evaluating transformer winding.

Online and offline diagnostic tests on transformers are essential to determine the development of possible failure before getting serious damage. Certain conventional and advanced tests can be conducted to identify assess the transformer condition [11]-[14]. The common test such as Partial Discharge (PD), tan(δ), Leakage-reactance measurement, and Transformer Turns Ratio (TTR). There are other advanced tests such as Frequency Dielectric Spectroscopy (FDS), Dissolved Gas Analysis (DGA), and the Frequency Response Analysis (FRA).

The TTR test measures the voltage ratio of each phase and then compares it with the ratio from the nameplate. The TTR test is a basic method to evaluate a transformer's winding condition. On the other hand, FRA is an advanced test method that can also evaluate the condition of the transformer winding but requires an experienced person to interpret the measurement [15]. It was mentioned in the CIGRE technical brochure [16] that FRA is used to detect the mechanical changes in the winding. Also, the IEEE standard (C57.149-2012) [17] and IEC 60076-18 [18] mentioned that FRA is a well-known method to determine the mechanical integrity of the transformer. Furthermore, the FRA is now used to investigate the non-mechanical changes within the transformer. FRA is shown to be sensitive towards non-mechanical parameters of the transformer in several works of literature. As an example, a comparison between FRA and FDS [19] presented that the ageing of oil-paper insulation in a transformer can be measured using FRA. In FRA, various statistical indicators are used to compute the variation between the normal response and faulty response. The common statistical indicators used are the Correlation Coefficient (CC), and the Absolute Sum of Logarithmic Error (ASLE).

This paper proposes the use of the FRA method to detect the inter-turns fault in the transformer winding. The fault is usually can be identified with the common TTR test. Both FRA and TTR tests are performed on all tap settings of a transformer winding with and without inter-turn fault in the winding. Consequently, results from the FRA test are analysed to determine if the fault can be detected using FRA. Next, the variations between normal and faulty responses are computed using statistical indicators. Finally, an acceptable limit for the statistical indicator is proposed in this paper which is established based on the acceptance limit of TTR as per IEEE standard.

The transformer short circuit fault (inter-turn fault) and FRA method are theoretically presented in Section I. Section II presents the FRA measurement setup, FRA frequency sub-bands and statistical indicators used to analyse the results. In Section III, the TTR test is introduced. In section IV, the results from the FRA and TTR are compared and analysed. In section V, based on the findings in the previous section, this paper proposed a statistical indicator limit for FRA measurement on inter-turn fault. Finally, the main conclusions are drawn in Section VI.

II. FREQUENCY RESPONSE ANALYSIS

FRA is a diagnostic method used to determine the mechanical integrity in transformer winding and core. The change is due to continuous electrical or mechanical stresses on the transformer which eventually causes physical defects. The FRA measures the overall resistance, inductance and capacitance of the transformer. The measurement is presented as a frequency response of the winding from 20 Hz to 2 MHz [20]. The measured response is then compared with the reference response or signature of the transformer which is measured when the unit is in good condition [9].

A. FRA inductive Inter-winding Test Configuration

FRA results vary depending on the test connections and other parameters. Thus, several researchers have tried to model different failures in transformers based on computer simulations and physical measurements. The aim is to evaluate the ability of various connections [21]-[23]. In most of the published works, the frequency response, based on the voltage ratio, showed a better representation of the fault compared to the input admittance-based response [24].

An international standard has listed four FRA test configurations and the inductive inter-winding test is one of them. In the inductive inter-winding test, the FRA analyser injects the small AC signal at one end of the HV winding, and measure the output from one end of the LV winding (same phase) with grounding. The input and reference signals are connected at HV and indicated by red and yellow lines. The output signal is connected to LV and indicated by the blue line. In the inductive inter-winding, the HV and LV windings should be grounded. The inductive inter-winding test configuration is shown in Fig. 2 [20]. This test configuration is also possible to be applied on three windings transformer but not on autotransformer since both windings (HV and LV) need to be separated and grounded.

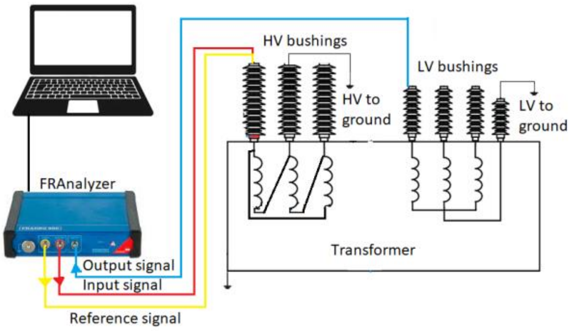

Fig. 2. Inductive inter-winding test configuration on a three-phase transformer with delta-wye connection.

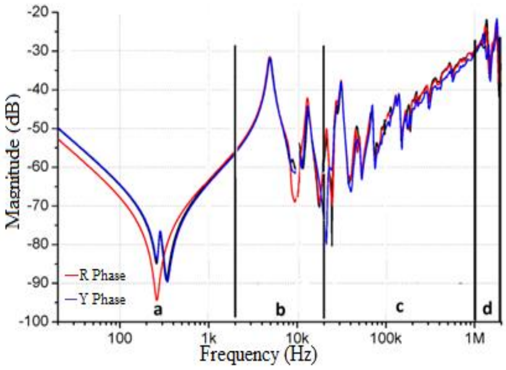

Fig. 3. FRA Sub-bands based

TABLE I: FAILURES SENSITIVITY AND FRA SUB-BANDS [26].

Sub-band	Frequency	Failure Sensitivity
a	<2 kHz	Open circuits, residual magnetism, shorted turns, and core faults.
b	2 kHz to 20 kHz	clamping loss, and Winding movement
c	20 kHz to 1 MHz	Tap windings damage
d	1 MHz to 2 MHz	Movement main tap windings, and ground impedances changes

B. FRA Sub-Band

The frequency response is unique for each transformer. It is determined by the transformer's size as well as various other factors such as winding design and arrangements [20]. The response can be divided into four separate sub-bands. Based on IEEE standard [17], the four frequency sub-bands are the low range, medium range, high range, and super-high- range. Any significant changes in the shape of the curves are mostly independent of the fault location [25]. This is shown in Fig. 3, and the responses are for the transformer phase R and phase Y. Fig. 3 is to show the FRA sub-bands demonstrated in IEEE standard. Every frequency sub-band is sensitive to a particular transformer condition or failure in Table I.

C. FRA Interpretation

FRA is mainly used for detecting winding mechanical damage in transformers. Nowadays, there is a growing interest in the FRA method due to its ability to indicate the mechanical fault in the transformer without internal visual inspection [27]. It comprises the measured response and the baseline response. Physical changes can be suspected if any deviation between the two responses is found [16].

The degree of the deviation between responses will indicate either the transformer has suffered extensive damage, slight deformation or normal condition. There are various statistical indicators which are applicable in the comparison of a transformer’s frequency responses. Some of the indicators are more suitable than others. The list of available indicators which have been proposed in FRA application is available in [28], [29]. Researchers have proposed various indicators to quantify the deviations between two FRA results. Statistical indicators such as error functions and Correlation Coefficient (CC) when applied on the frequency sub-bands can provide a value on the differences [30].

CC is used to calculate the variation between two data variables [31], defined as

$$\mathrm{CC} = \frac{\sum_{i=1}^{N} X_i \times Y_i}{\sqrt{\sum_{i=1}^{N} X_i^2 \times \sum_{i=1}^{N} Y_i^2}} \tag{1}$$

where X_i and Y_i are the values in dB for each frequency point i. N is the number of frequency points in each frequency response. This is typically 1000 points which are logarithmically spaced between 20 Hz and 2 MHz. CC result varies from 0 to 1. When CC = 1, the two data sets are correlated or identical, whereas when CC = 0, there is no correlation between the two data sets. On the other hand, the negative correlation means that one variable increases while the other decreases. In simple words, they are moving in opposite directions. CC has a flaw namely it will indicate an identical correlation between two responses when $X_i = aY_i$ [32], [33]. $X_i = aY_i$ means responses X and Y have similarities in the slope but both appear in different magnitudes.

The deviation between responses can be calculated using other statistical indicators. Standard deviation (SD), for example, is used in [28], [34]. SD is defined as the deviation of one data set from its mean value [32]:

$$\mathrm{SD} = \sqrt{\frac{\sum_{i=1}^{N} \left(X_i - Y_i\right)^2}{N-1}} \tag{2}$$

SD is also known as root mean square error (RMSE).

Another indicator is the Mean Square Error (MSE), defined as

$$\mathrm{MSE} = \frac{\sum_{i=1}^{N} \left(X_i - Y_i\right)^2}{N} \tag{3}$$

MSE has inherent characteristics that can suppress small errors and amplify large errors. Ideally, when two data sets or frequency responses are a match, MSE is zero [32].

Absolute Sum of Logarithmic Error (ASLE) is another indicator represented by (4).

$$\mathrm{ASLE} = \frac{\sum_{i=1}^{N} \left|X_i - Y_i\right|}{N} \tag{4}$$

Here, ASLE is defined to evaluate two sets of data on a logarithmic scale. Thus, it can prevent the weakness of MSE in ill-scaling property [31]. The standard calculated value of ASLE is 0 if both data sets and both frequency responses are identical. ASLE is believed to be an efficient statistical indicator. According to [27], [32], it is perfect to detect the variation between the two data sets.

Maximum minimum (MM) is a statistical indicator:

$$\mathrm{MM} = \frac{\sum_{i=1}^{N} \min\left(X_i, Y_i\right)}{\sum_{i=1}^{N} \max\left(X_i, Y_i\right)} \tag{5}$$

This indicator is sensitive to slight changes and its ideal value is 1. MM is considered less sensitive to variations in the shape of resonances with a slight deviation in their amplitudes [27]. It is only the maximum and minimum values for each pair of data points.

The above-mentioned statistical indicators are parametric methods that are commonly employed in FRA. It is also worth mentioning that other pieces of literature have presented the use of a non-parametric method for FRA such as Spearman CC and Friedman test as presented in [35]. Additionally, it is also important to note that the statistical indicator values are dependent on the size of the data set. The size of data set or window width in FRA result can influence the analysis significantly as presented in [36].

III. TRANSFORMER TURNS RATIO TEST

The transformer turns-ratio test is a no-load low AC-voltage test that can determine the ratio between the high and low voltage windings. It is performed in all taps of every winding. The connection of the transformer-turns-ratio test is shown in Fig. 4 [37].

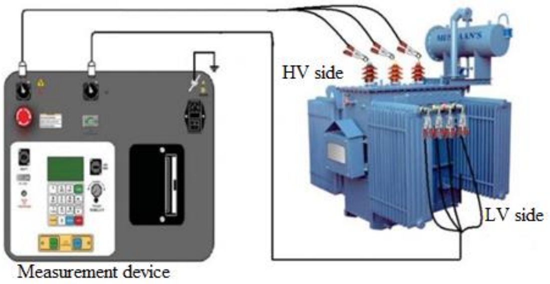

Fig. 4. Turns Ratio Measurement configuration [33]

The Transformers-turns-ratio test has two steps. First, the turn's ratio V_{ratio} based on the voltages between the voltage of primary winding, V_p and secondary winding, V_s is measured according to

$$V_{\text{ratio}} = \frac{V_p}{V_s} = \frac{N_p}{N_s} \tag{6}$$

Second, the error ratio $\Delta_{\text{ratio}}\%$ between the actual ratio from the nameplate and the measured ratio of the voltage ratio is calculated as

$$\Delta_{\text{ratio}}\% = \left| \frac{V_{\text{ratio maesured}} - V_{\text{ratio nameplate}}}{V_{\text{ratio maesured}}} \right| \times 100\% \tag{7}$$

The percentage ratio error or difference $\Delta_{\text{ratio}}\%$ shall not exceed the limits given by IEEE standards which is (0.5%) [18].

IV. FRA AND TTR MEASUREMENT RESULTS

This section presents the results obtained from the TTR and FRA tests. The transformer, selected in this study, is a complete three-phase distribution transformer with voltage and power ratings of 11/0.415 kV and 500 kVA respectively. It is a Dyn11 connection with a de-energized tap changer. The transformer has been removed from the main tank to create an inter-disc fault on the winding for this study as shown in Fig. 5. Although this study used a distribution size transformer, the methodology or scenario can be applied on large size transformer provided it has tap changer.

Fig. 5. Three-phase 500 kVA distribution transformer used in this study.

The inter-disc fault is created in phase A by shorting two tap terminals of phase A using a short piece of wire as shown in Fig. 6. Fig. 6 (top) represents the winding in normal condition with tap changer at tap 1 (connecting terminal 4 and 5) while Fig. 6 (bottom) is when tap 2 (connecting terminal 3 and 5) is shorted while tap changer is still in place. The results from FRA and TTR test are compared and analysed to determine FRA statistical indicator values which is equivalent to 0.5% acceptable limit in TTR.

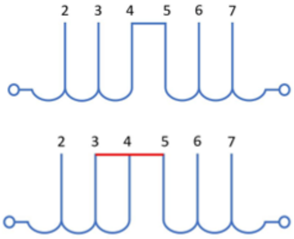

Fig. 6. Shorted-tap conductor in phase A, (top) Normal condition (bottom) Shorted at tap 2.

A. FRA Measurement Results

FRA measurement is conducted using an inductive inter-winding test configuration instead of the common end-to-end winding. The measurement is also performed when the windings are not immersed in oil (as in Fig. 5). However, this will not affect the analysis as all responses are compared under the same condition. The frequency response for normal condition, short at tap 2, short at tap 3 (connecting terminal 3 and 6), short at tap 4 (connecting terminal 2 and 6) and short at tap 5 (connecting terminal 2 and 7) are shown in Fig. 7.

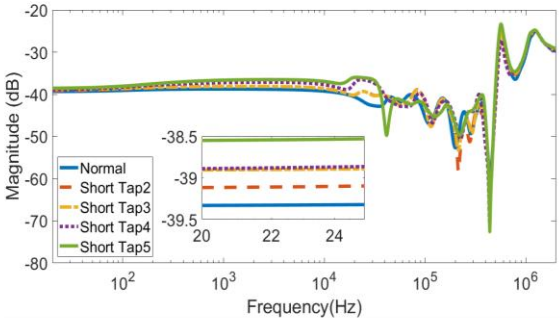

Fig. 7. FRA inductive inter-winding at normal vs. short-turns at all taps.

TABLE II: FRA RESULTS FROM 20 HZ TO 60 HZ

Freq. (Hz)	Normal (dB)	Tap 2 short (dB)	Tap 3 short (dB)	Tap 4 short (dB).	Tap 5 short (dB)
20	-39.33	-39.12	-38.95	-38.89	-38.55
25	-39.32	-39.10	-38.89	-38.86	-38.53
30	-39.31	-39.08	-38.88	-38.84	-38.51
35	-39.30	-39.06	-38.86	-38.81	-38.49
40	-39.28	-39.03	-38.84	-38.76	-38.46
45	-39.26	-39.00	-38.82	-38.73	-38.43
50	-39.25	-38.98	-38.80	-38.69	-38.40
55	-39.23	-38.96	-38.78	-38.65	-38.37
60	-39.22	-38.93	-38.77	-38.61	-38.33

Fig. 7 shows that there is some variation between healthy and faulty responses due to the fault. These changes appear in almost the whole frequency region (20 Hz to 400 kHz), which proves that FRA can detect a failure in turns ratio. To further analyses the results, the frequency region from 20 Hz to 60 Hz is selected for comparison with the TTR result. This is because the TTR test injects 50 Hz or 60 Hz signals during the measurement. The data from FRA measurement between 20 Hz to 60 Hz is as shown in Table II.

It can be noted that the increase in the magnitude is due to inter-disc fault. As an example, the magnitude at 50 Hz at normal conditions is –39.25 dB while the magnitude due to shorted tap5 is –38.40 dB. The increase in magnitude from 20 Hz to 60 Hz is shown in Fig. 8.

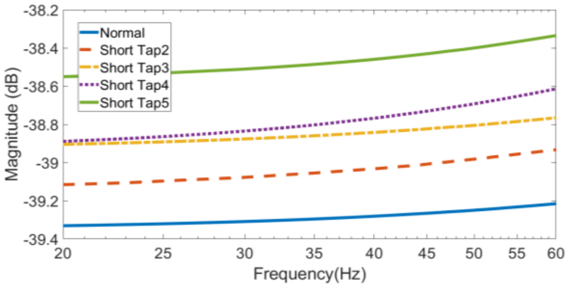

Fig. 8. FRA results for the frequency range of 20 Hz to 60 Hz.

B. Statistical Analysis

In this section, the variation between the FRA responses of normal and inter-turn is calculated, and the results are shown in Table III. From the results, CC and MM do not indicate significant variation due to the fault. On the other hand, ASLE, MSE and SD show considerable change. Here, the ASLE value is increasing gradually from the winding short circuit at tap 2 to that at tap 5. MSE also indicated an increasing trend from 0.0628 to 0.6833 for the winding short circuit at tap 2 to that at tap 5. As in ASLE and MSE, SD also shows a rising trend. Different statistical aspects are presented in Fig. 9.

TABLE III: STATISTICAL INDICATORS RESULTS FOR NORMAL AND SHORT TURNS

Indicator	Normal vs. Tap 2 short	Normal vs. Tap 3 short	Normal vs. Tap 4 short	Normal vs. Tap 5 short
CC	0.9996	0.9998	0.9999	0.9999
ASLE	0.2495	0.4385	0.5173	0.8259
MSE	0.0628	0.1923	0.2705	0.6833
MM	1.0064	1.0113	1.0133	1.0215
SD	0.2158	0.4652	0.5516	0.8767

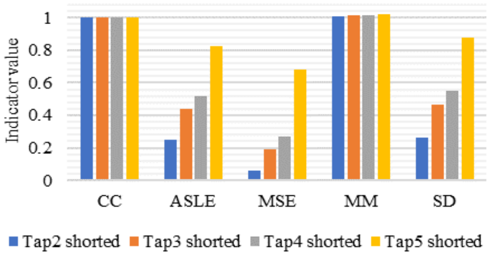

Fig. 9. Statistical indicators sensitivity to responses variation due to shorted turns.

C. Turn Ratio Measurement Results

TTR measurement results are given in Table IV. It can be noted that the voltage ratio V_{ratio} in phase "A" decreases due to shorted turns in the same phase. The percentage difference Δ% between the measured and calculated voltage ratios increases from the short at tap 2 to that at tap 5. Other winding phases are unaffected by the fault. The measured voltage ratio against the fault for phase A is plotted in Fig. 10. The decreasing value of the measured voltage ratio is due to the reduction in the number of winding turns.

Correlation between TTR and FRA results can be seen by observing the measured values on phase A at 50 Hz. The voltage ratio in Table IV decreases from 46.217, at normal condition, to 42.772 at the short circuit at tap 5. Similarly, the magnitude presented in Table II decreases from –39.25 dB at, normal conditions, to 38.40 dB at the short circuit at tap 5.

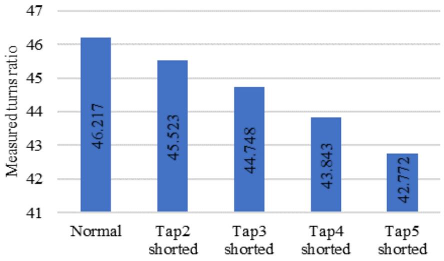

Fig. 10. The turn ratio results for normal and inter-turns at phase A

TABLE IV: THE MEASURED VOLTAGE RATIO AND THE PERCENTAGE DIFFERENCE

Condition	Phase A		Phase B		Phase C	
	V_{ratio}	Δ%	V_{ratio}	Δ%	V_{ratio}	Δ%
Normal	46.217	0.03	46.218	0.04	46.218	0.04
Tap 2 shorted	45.523	1.47	46.219	0.04	46.217	0.03
Tap 3 shorted	44.748	3.14	46.217	0.03	46.217	0.03
Tap 4 shorted	43.843	5.10	46.219	0.04	46.217	0.03
Tap 5 shorted	42.772	7.42	46.217	0.03	46.217	0.03

V. PROPOSED INDICATOR LIMIT

From the findings in the previous section, this paper proposes a statistical indicator limit for FRA measurement on inter-turn fault. The indicator limit can be used for estimating the condition of winding turns ratio based on FRA measurement instead of the TTR measurement. It is based on the TTR acceptance limit of 0.5%. From $\Delta V_{\text{ratio}}\%$ in (7), the voltage ratio limit $V_{\text{ratio limit}}$ is calculated as

$$0.5\% = \left(1-\frac{V_{\text{ratio limit}}}{46.217}\right)\times 100\% \qquad (8)$$

In (8), 0.5% is the TTR acceptance value as given in IEEE std C57.152-2013 [16] while 46.217 is the nameplate voltage ratio. From equation (8), the calculated $V_{\text{ratio limit}}$ is 45.986 at 0.5% acceptance limit.

This value is then marked in the plot of statistical indicator versus the voltage ratio as shown in Fig. 11, Fig. 12 and Fig. 13. Each plot shows a calculated statistical indicator value for each of the voltage ratios for normal to short circuits at tap 5 conditions. The Curve-fitting function is then used to estimate a linear relationship between the statistical indicator and voltage ratio. The vertical line indicates $V_{\text{ratio limit}}$ while the horizontal line indicates the statistical indicator value at $V_{\text{ratio limit}}$. The statistical indicator value at $V_{\text{ratio limit}}$ is the proposed limit.

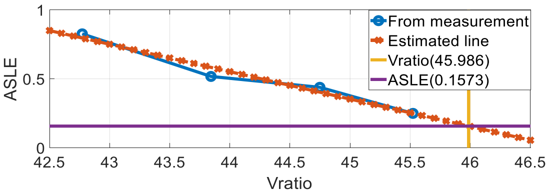

Fig. 11. Estimated limit for ASLE.

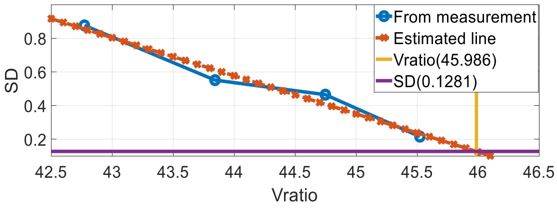

Fig. 12. Estimated limit for SD.

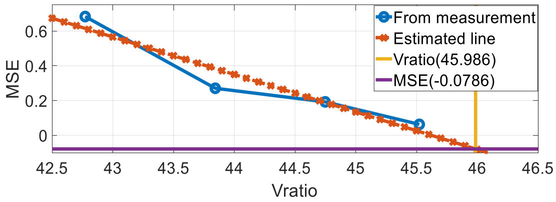

Fig. 13. Estimated limit for MSE.

For ASLE in Fig. 11, the estimated limit is 0.1573. As an example, the short circuit at tap 2 has ASLE value of 0.249 which is larger than the proposed ASLE limit and thus, correctly indicates that the winding is faulty. This is similar for SD in Fig. 12 in which the proposed estimated limit is 0.1281. However, the limit for MSE in Fig. 13 is –0.0786 which is a negative value therefore not suitable to be used as a limit.

VI. CONCLUSION

FRA measurement shows that there are changes in the inductive inter-winding response when applying inter-turn fault. Investigation on the response between 20 Hz and 60 Hz indicates that the magnitude increase is dependent on the level of fault. The variation between normal condition and short circuit at tap 5 is larger than the variation between normal condition and short circuit at tap 2. The TTR measurement shows that the voltage ratio has decreased since the fault has reduced the number of effective turns. For the statistical indicators used in this study, it is concluded that CC and MM were not sensitive to the variation between the responses. ASLE, MSE and SD on the other hand were sensitive and showed a trend due to the fault. These indicators were plotted against the voltage ratio. Statistical indicator limit was proposed based on voltage ratio for 0.5% TTR acceptance limit. Findings showed that only ASLE and SD limits can be used to evaluate winding conditions. The findings presented in this paper is based on once case study of a distribution transformer. In future, this concept can further apply on other different transformer sizes to verify the proposed indicator limit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Ali Salman and Mohd Fairouz conducted the research, analysed data and wrote the paper. Salem and Ali Jber edited the paper. Mohd Aizam assist in conducting the electrical test at the laboratory; all authors had approved the final version.

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