TRANSFORMER CORE AND WINDING CONDITIONS EVALUATION FROM SFRA MEASUREMENT RESULTS USING CROSS-CORRELATION COEFFICIENT FUNCTION FOR TNB DISTRIBUTION TRANSFORMERS

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Transformer Core and Winding Conditions Evaluation from SFRA Measurement Results using Cross-correlation Coefficient Function for TNB Distribution Transformers

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***Abstract*--Distribution transformers in TNB (Tenaga Nasional Berhad) Malaysia are exposed to the thermal and electrical stresses. Those stresses are effecting to the main mechanical active parts in transformer such as core and winding. In field, lightning strikes and cable faults may cause problem due to transformer core and winding. SFRA diagnosis is made based on the comparison between two SFRA responses and any significant difference in low, middle and high frequency sub-bands region would potentially indicate mechanical or electrical problem due to core and winding of transformer. Instead of using graphical comparison, numerical technique such as Cross-correlation Coefficient Function (CCF) can be used to interpret the SFRA results in a proper way. The aim of this paper is to assess the condition of TNB distribution transformer by using SFRA method in line with the interpretation from the CCF technique.**

***Index Terms*--Correlation Coefficient, Core, Distribution Transformer, Sweep Frequency Response Analysis, Winding.**

I. INTRODUCTION

There are varieties of faults conditions occur in power system networks such as lightning strikes, switching transients, cable strikes, apparatus failures and other incidents [1]. These faults will develop short-circuit current to be experienced by the apparatus in the power system network such as power transformer, three-phase motor and three-phase generator [2]. Power transformers are designed to adapt or withstand this short-circuit current, but the strong electrodynamics forces resulting from short-circuit can give defects to the transformer windings and core [3]. In the power transformer, the active part where the transformation takes place consists of core and winding [4]. Hence, serious attention is needed by the asset management to have monitoring systems for fault diagnosis to the power transformers whether it have suffered from the damage that could limit its lifetime and capability to withstand short-circuit current [4].

Fault diagnosis that have been used in power transformer are recovery voltage measurement (RVM), dissolved gas in oil analysis (DGA), and the frequency response analysis (FRA). RVM method is used to detect the conditions of oil-paper insulation and the water content of the insulation. In this method, a power transformer outage is required to carry out the test; meanwhile the test results give an indication of the state of the oil/paper insulation structure of the power transformer. However, the drawbacks in this method are a long outage may be required and the unreliability in the interpretation of the results [1]. DGA analyzes the percentages of ingredient gases in insulating oil, and provides the type of fault in power transformer according to the composition of gases. DGA has been widely used to periodically monitor status of power transformers. However, DGA is not capable of detecting precise electrical and/or mechanical faults, because they affect the dissolved oil in an indirect manner [5]. To overcome this limitation, FRA is capable for detecting failures in the core and winding geometries of power transformer [6]. There are two different methods used to carry out the FRA measurement: the sweep frequency response analysis (SFRA) and impulse frequency response analysis (IFRA) [3].

In this paper, the SFRA method is used because of it usage on detecting transformer winding deformation of TNB Distribution transformers [7]. SFRA method are generates magnitude and phase responses in frequency domains with measured input/output of voltage/current signals as shown in Fig. 1[8]. SFRA method is purely a comparative method, which compares the measured responses with the reference fingerprints. However, the fingerprints are rarely available, especially in-service transformers. Thus other information (such as comparison between identically constructed transformers and comparison between phases inside transformer) has to be taken for diagnosis [12]. Fig. 2, shows the comparison between SFRA measurement results of reference transformer and transformer under test. In general, the greater the difference between the two results, the greater movement in the transformer.

For interpret the SFRA measurement results, researchers are working on analyzing techniques, by involving proper mathematical and statistical evaluation. These techniques would help to analyze different types of faults with respect to

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different types of transformers. Birlasekaran has proposed three analyzing techniques in his paper i.e. signature, difference, and quantitative [9]. Nirgude *et. al* has presented three different statistical indicators for comparing the results of SFRA measurements on power transformers. The indicators are cross-correlation coefficient functions (CCF), standard deviation (SD) and absolute sum of logarithmic error (ASLE) [10]-[12]. CCF is used in this paper to interpret the SFRA measurement results of tested TNB distribution transformer.

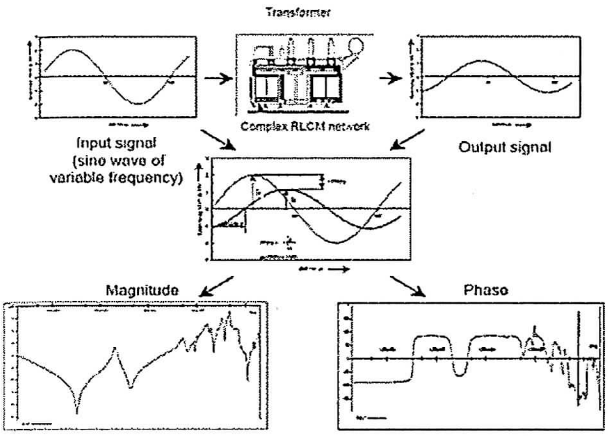

Fig. 1. SFRA Concept of Measurement. [7]

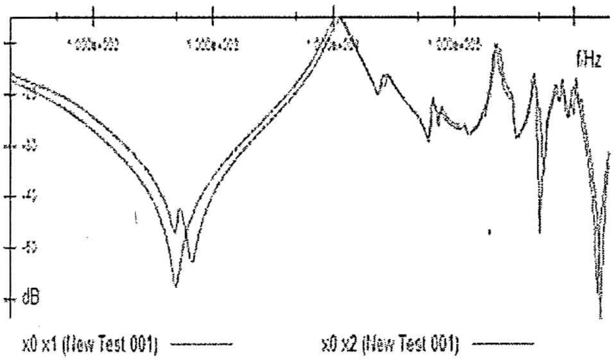

Fig. 2. SFRA Measurement Results Comparison.

II. MEASUREMENT METHOD

The Omicron FRAnalyzer is a sweep frequency response analysis (SFRA) device that has been used for the diagnosis of mechanical movement in the TNB in-service transformers. Fig. 3 shows the connection of Omicron FRAnalyzer to the tested transformer. The device generates a sinusoidal voltage at a selected frequency (from 20 Hz to 20 MHz) and measured the input voltages, amplitude and phase, on two input channels of "Reference" and "Measure". Subsequently, the transfer function is determined regarding to the ratio of input and output results and the common way of representing the transfer function is based on bode plot diagrams; where both magnitude and phase response are illustrated. In majority of studies, the magnitude response is commonly used on diagnosing and interprets the transformer problems [7-12].

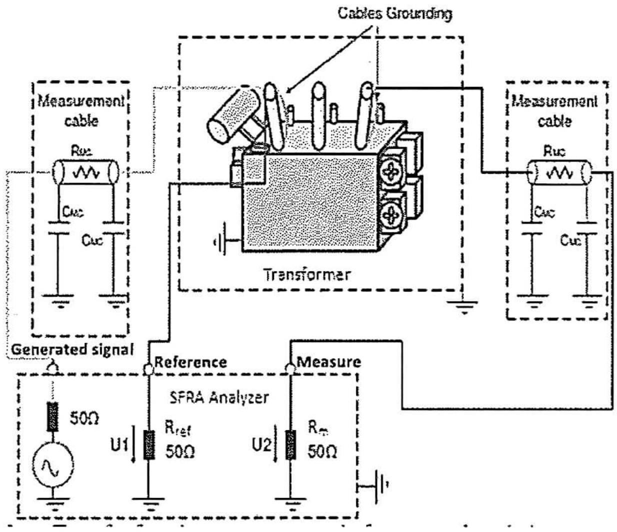

Fig. 3. The Omicron FRAnalyzer Terminal Connection [8].

III. FREQUENCY RANGES OF SFRA

The magnitude response of a tested transformer gained from SFRA is basically in frequency domain, which means that each ranges of frequency are related to the transformer transfer function. The transfer function itself indicates the response from each complex parameter inside the transformer. The sweep frequency generated is between 20 Hz and 20 MHz. For the application of transformer mechanical movement detection especially core and winding, these frequency ranges are used according to Table 1 [5]-[8].

TABLE 1
FREQUENCY RANGES USED IN SFRA INTERPRETATION

Frequency Ranges	Sensitive to Elements
Below to 10 kHz	In this range phenomena linked with the transformer core and magnetic circuits are found.
10 kHz to 500 kHz	In this range phenomena linked with radial relative geometrical movements between windings are detected.
200 kHz to 1 MHz	In this range axial deformations of each single winding are detectable.

IV. STATISTICAL METHODS USED

SFRA is a comparative method, where both reference response and measured response are compared. The response of the measured transformer can be compared by three categories of references; tested transformer itself (fingerprints), identically transformer (sister unit transformer) and symmetrical winding comparison [3]. The comparison responses are then being interpreted by using conventional technique; graphical analysis. This technique requires trained experts to interpret the response for identifying any problems and faults related to the tested transformer. There have an attempts made by other researchers to overcome this interpretation issues by using statistical methods, therefore inexperienced personnel could be involved in. Cross-correlation Coefficient Function (CCF) equation is shown below.

$$CCF_{(x,y)} = \frac{\sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2 \times (Y_i - \bar{Y})^2}} \quad (1)$$

X(i) and *Y(i)* are *i*th elements of the reference fingerprints and measured frequency response, respectively, using SFRA. *N* is the total number of samples in the frequency response. In the analyzing, CCF is designed to approach from 1 to 0. If the CCF value closed to 1, it define the shape of *X(i)* and *Y(i)* are similar to each other. Meanwhile if the CCF value approximate to 0, there are deviation occur from the graph and could be a sign of defect in the transformer.

V. RESEARCH RESULTS AND DISCUSSIONS

In this research work, three case studies from TNB in-service transformers are discussed for the detection of mechanical movement based on SFRA measurement results. Statistical technique, CCF is used to interpret the SFRA results. In each case study, the comparisons of the SFRA measurement results are done by using symmetrical winding comparison type.

A. Case Study 1: PPU Damansara Height T1 Transformer, 30 MVA, 33/11 kV

In this case, the transformer has been in-service for almost 30 years and not indicates any problem or defects in the operation period. SFRA measurement carried out on both HV and LV windings. As shown in Fig. 4 and Fig. 5, illustrates the SFRA measurement results for HV winding (H1H2 phase to H2H3 phase) and LV winding (x0x1 phase to x0x2 phase). As it can be seen, comparison for these two curves in each HV and LV winding are very similar which indicate a good mechanical condition in transformer core and winding. The calculated of CCF from the SFRA measurement results are given in Table 2. According to Table 2, the CCF indicates no such obvious deviation occur from the SFRA measurement results in each frequency ranges and for both HV and LV windings. The CCF results are between ranges of 0.9986 to 0.9998.

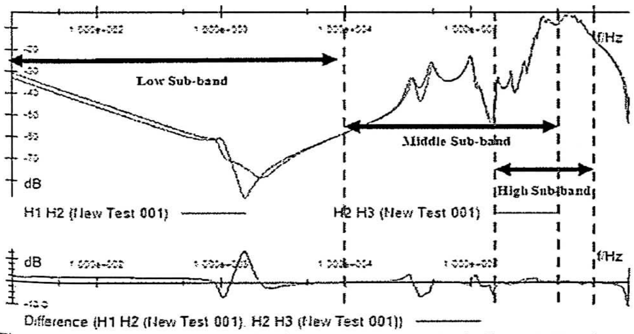

Fig. 4. SFRA measurement results for case study 1 HV winding (H1H2 phase compared to H2H3 phase).

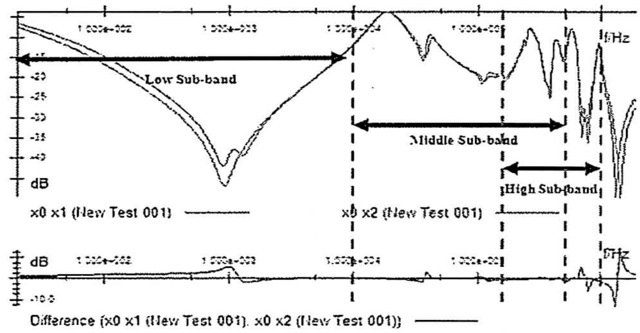

Fig. 5. SFRA measurement results for case study 1 LV winding (x0x1 phase compared to x0x2 phase).

TABLE 2
STATISTICAL INDICATORS FOR CASE STUDY 1

Frequency Ranges	Winding	Phases Comparison	CCF Results
20 Hz - 10 kHz	HV	H1H2 to H2H3	0.9998
		H1H2 to H3H1	0.9998
		H2H3 to H3H1	0.9994
	LV	x0x1 to x0x2	0.9962
		x0x1 to x0x3	0.9967
		x0x2 to x0x3	0.9866
10 kHz - 500 kHz	HV	H1H2 to H2H3	0.9987
		H1H2 to H3H1	0.9986
		H2H3 to H3H1	0.9974
	LV	x0x1 to x0x2	0.9940
		x0x1 to x0x3	0.9963
		x0x2 to x0x3	0.9990
200 kHz to 1 MHz	HV	H1H2 to H2H3	0.9976
		H1H2 to H3H1	0.9978
		H2H3 to H3H1	0.9975
	LV	x0x1 to x0x2	0.9932
		x0x1 to x0x3	0.9930
		x0x2 to x0x3	0.9950

B. Case Study 2: PPU Seksyen 23 T2 Transformer, 30 MVA, 33/11 kV

In this case, the transformer has been in-service for almost 18 years and with situation of transformer tripped on Buchholtz and Differential which suggested the occurrence of internal fault. This is supported by DGA where results showed the occurrence of High Energy Arcing with little involvement of paper [13]. The SFRA measurement carried out on both HV and LV windings. As shown in Fig. 6 and Fig. 7, illustrates the SFRA measurement results for HV winding (H1H2 phase to H2H3 phase) and LV winding (x0x1 phase to x0x2 phase). As it can be seen, comparison for these two curves in HV winding is having a huge changes or different in low and high frequency range which indicate a defect or problem related to the mechanical condition in transformer core and winding. Meanwhile in LV winding, the changes only occur in low frequency range that only related to the transformer core problem. The calculated of CCF from the SFRA measurement results are given in Table 3. According to Table 3, the CCF results for low and high frequency sub-band ranges shows an obvious deviation occurred. In low frequency sub-band, CCF results indicate a problem at LV winding related to the transformer core condition especially in the middle limb of core. Meanwhile in the high frequency sub-band, CCF results indicate a problem related to the axial deformation of transformer winding at HV winding.

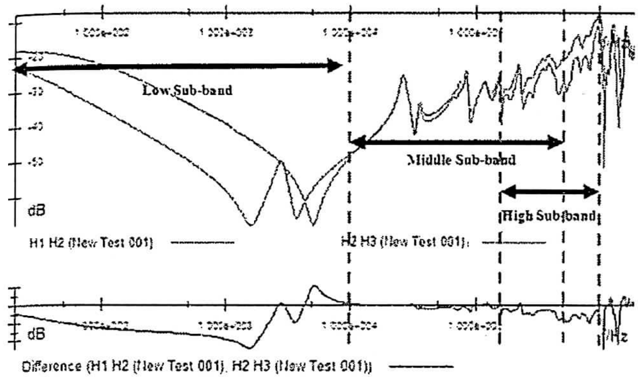

Fig. 6. SFRA measurement results for case study 2 HV winding (H1H2 phase compared to H2H3 phase).

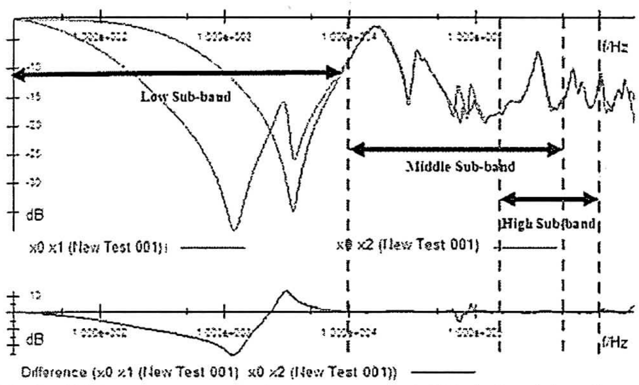

Fig. 7. SFRA measurement results for case study 2 LV winding (x0x1 phase compared to x0x2 phase).

TABLE 3
STATISTICAL INDICATORS FOR CASE STUDY 2

Frequency Ranges	Winding	Phases Comparison	CCF Results
20 Hz - 10 kHz	HV	H1H2 to H2H3	0.9219
		H1H2 to H3H1	0.9999
		H2H3 to H3H1	0.9218
	LV	x0x1 to x0x2	0.7794
		x0x1 to x0x3	0.9993
		x0x2 to x0x3	0.7688
10 kHz - 500 kHz	HV	H1H2 to H2H3	0.9769
		H1H2 to H3H1	0.9811
		H2H3 to H3H1	0.9782
	LV	x0x1 to x0x2	0.9918
		x0x1 to x0x3	0.9918
		x0x2 to x0x3	0.9852
200 kHz to 1 MHz	HV	H1H2 to H2H3	0.7416
		H1H2 to H3H1	0.5692
		H2H3 to H3H1	0.7212
	LV	x0x1 to x0x2	0.9723
		x0x1 to x0x3	0.9642
		x0x2 to x0x3	0.9857

C. Case Study 3: PPU Kelibang T2 Transformer, 7.5 MVA, 33/11 kV

In this case, the transformer has been in-service for almost 16 years and with situation of standby earth fault relays (SBEF) at respective transformer's tripped the local 11 kV breaker when the transformer were connected in parallel. Meantime, DGA results for this transformer indicates a high concentration of Hydrogen, Ethylene and Acetylene this could result an arcing had occurred. CO_2/CO ratio also indicated that paper was also involved in the arcing [13]. The SFRA measurement carried out on both HV and LV windings. As shown in Fig. 8 and Fig. 9, illustrates the SFRA measurement results for HV winding (H1H2 phase to H2H3 phase) and LV winding (x0x1 phase to x0x2 phase). As it can be seen, comparison for these two curves in HV winding is having a changes or different in middle and high frequency range which indicate a defect or problem related to the mechanical condition in transformer winding. Meanwhile in LV winding, the changes only occur in high frequency range that only related to the transformer winding problem. The calculated of CCF from the SFRA measurement results are given in Table 4. According to Table 4, the CCF results for high frequency sub-band ranges shows an obvious deviation occurred while others remain slight changes. In high frequency sub-band, CCF results indicate a problem related to the axial deformation of transformer winding condition especially in the middle limb of core at LV winding.

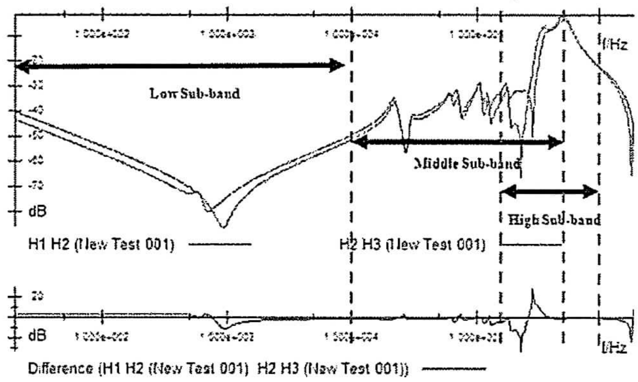

Fig. 8. SFRA measurement results for case study 3 HV winding (H1H2 phase compared to H2H3 phase).

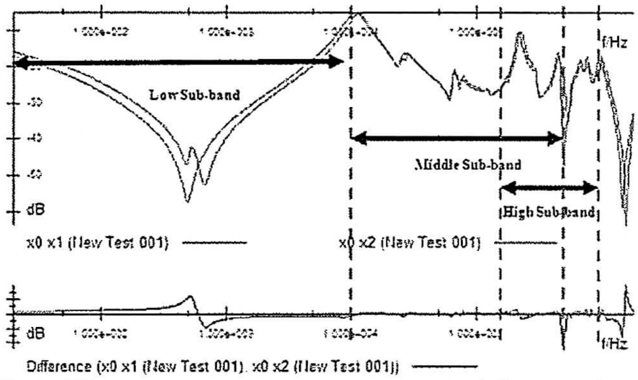

Fig. 9. SFRA measurement results for case study 3 LV winding (x0x1 phase compared to x0x2 phase).

TABLE 4
STATISTICAL INDICATORS FOR CASE STUDY 3

Frequency Ranges	Winding	Phases Comparison	CCF Results
20 Hz - 10 kHz	HV	H1H2 to H2H3	0.9747
		H1H2 to H3H1	0.9988
		H2H3 to H3H1	0.9844
	LV	x0x1 to x0x2	0.9748
		x0x1 to x0x3	0.9970
		x0x2 to x0x3	0.9890
10 kHz - 500 kHz	HV	H1H2 to H2H3	0.9494
		H1H2 to H3H1	0.9925
		H2H3 to H3H1	0.9712
	LV	x0x1 to x0x2	0.9819
		x0x1 to x0x3	0.9966
		x0x2 to x0x3	0.9842
200 kHz to 1 MHz	HV	H1H2 to H2H3	0.9534
		H1H2 to H3H1	0.9731
		H2H3 to H3H1	0.9431
	LV	x0x1 to x0x2	0.8934
		x0x1 to x0x3	0.9910
		x0x2 to x0x3	0.8931

VI. CONCLUSION

In this paper, Cross-correlation Coefficient Function (CCF) as one of the statistical methods are presented and evaluated for comparing the results of SFRA measurements. They applied to a number of healthy and faulty transformers as suitable case studies. The results show that, CCF is good for explaining the variation of SFRA measurement results by using the range of result from 1 to 0. For the next work, the validations of the CCF results from the transformer untanking process are needed.

VII. ACKNOWLEDMENT

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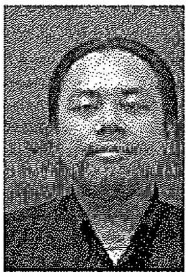
IX. BIOGRAPHIES



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