Scientific Research

Detection of Mechanical Deformation in Old Aged Power Transformer Using Cross Correlation Co-Efficient Analysis Method

Asif Islam[1], Shahidul Islam Khan[2], Aminul Hoque[2]
[1]*Energypac Engineering Ltd., Dhaka, Bangladesh*
[2]*Department of Electrical & Electronic Engineering, Bangladesh University of Engineering & Technology, Dhaka, Bangladesh*
E-mail: *asif038@gmail.com, shahidul@eee.buet.ac.bd, aminulhoque@eee.buet.ac.bd*

Abstract

Detection of minor faults in power transformer active part is essential because minor faults may develop and lead to major faults and finally irretrievable damages occur. Sweep Frequency Response Analysis (SFRA) is an effective low-voltage, off-line diagnostic tool used for finding out any possible winding displacement or mechanical deterioration inside the Transformer, due to large electromechanical forces occurring from the fault currents or due to Transformer transportation and relocation. In this method, the frequency response of a transformer is taken both at manufacturing industry and concern site. Then both the response is compared to predict the fault taken place in active part. But in old aged transformers, the primary reference response is unavailable. So Cross Correlation Co-Efficient (CCF) measurement technique can be a vital process for fault detection in these transformers. In this paper, theoretical background of SFRA technique has been elaborated and through several case studies, the effectiveness of CCF parameter for fault detection has been represented.

1. Introduction

Nowadays, reliability is an inevitable part of power system studies and operation, due to significant increase in the number of industrial electrical consumers. Power transformer is one of the major and critical elements in power system [1] in the area of reliability issue, since their outage may result in costly and time-consuming repair and replacement. Power transformers are specified to withstand the mechanical forces arising from both shipping and subsequent in-service events, such as faults and lightning. Once a transformer is damaged either heavily or slightly, the ability to withstand further incidents or short circuit test [2] becomes reduced. There is clearly a need to effectively identify such damage. A visual inspection is costly and does not always produce the desired results or conclusion [3-10]. During a field inspection, the oil has to be drained and confined space entry rules apply. Often, a complete tear down is required to identify the problem. An alternative method is to implement field-diagnostic techniques that are capable of detecting damage such as Frequency Response Analysis (FRA) [11-16].

FRA is a generally well-known testing technique within the industry to determine a transformer winding deformation, e.g. coils, turns, layers, HV leads, .etc, owning to short-circuit currents (faults), impact during transportation and aging [11]. Dick and Erven were the first to use the FRA method to detect the transformer winding deformation in 1978 [10]There are basically two techniques used for FRA measurements on power transformers; Low Voltage Impulse (LVI) based FRA and Sweep Frequency Response Analysis (SFRA) [16]. The two techniques are also termed FRA-I (impulse method) and FRA-S (swept-frequency method) [17]. The common strategy for both methods [18] is that the transformer impedance is measured at several different frequencies. The impedance will vary from one frequency to another due to the internal constitution of the transformer.

2. SFRA Theory

When a transformer is subjected to FRA testing, the leads are configured in such a manner that four terminals are used. These four terminals can be divided into two unique pairs [6,8,19], one pair for the input and the other pair for the output. These terminals can be modeled in a two-terminal pair or a two-port network configuration. **Figure 1** illustrates a two-port network where Z_{11}, Z_{22}, Z_{12} and Z_{21} are the open-circuit impedance parameters.

The transfer function of this network [20] is represented in the frequency domain and is denoted by the Fourier variable $H(j\omega)$, where $(j\omega)$ denotes the presence of a frequency dependent function and $\omega = 2\pi f$. The Fourier relationship for the input/output transfer function is given by Equation (1).

$$H(j\omega) = \frac{V_{output}(j\omega)}{V_{input}(j\omega)} \tag{1}$$

when a transfer function is reduced to its simplest form, it generates a ratio of two polynomials. The main characteristics, such as half-power and resonance of a transfer function occur at the roots of the polynomials. The roots of the numerator are referred to as "zeros" and the roots of the denominator are "poles" [21]. Zeros produce an increase in gain while poles cause attenuation.

The goal of FRA is to measure the impedance model of the test specimen. When the transfer function $H(j\omega)$ is measured, it does not isolate the true specimen impedance $Z(j\omega)$. The true specimen impedance $Z(j\omega)$ is the RLC network which is positioned between the instrument leads and it does not include any impedance supplied by the test instrument. **Figure 2** illustrates the RLC circuit with shunt resistor.
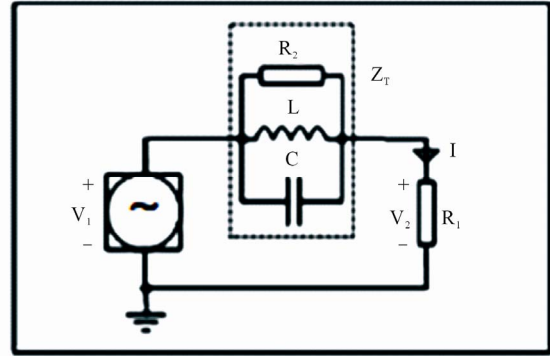
From the figure, Voltage division formula gives

$$V_2(j\omega) = V_1(j\omega) \frac{R1}{R1 + \cfrac{1}{\cfrac{1}{R2} + \cfrac{1}{j\omega L} + j\omega C}}$$

The transfer function is:
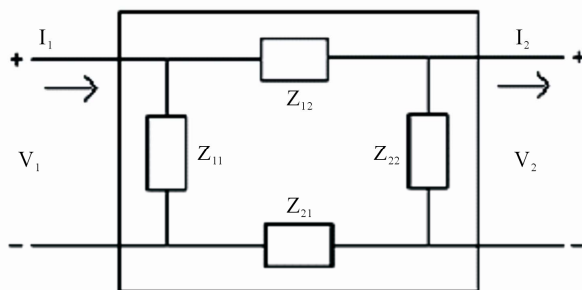
Figure 1. Two port network.

Figure 2. RLC circuit and shunt resistor.

$$H(j\omega) = \frac{V_2(j\omega)}{V_1(j\omega)} = \frac{R_1}{R_1 + \cfrac{1}{\cfrac{1}{R_2} + \cfrac{1}{j\omega L} + j\omega C}}$$

$$= \frac{R_1\left(\cfrac{1}{R_2} + \cfrac{1}{j\omega L} + j\omega C\right)}{R_1\left(\cfrac{1}{R_2} + \cfrac{1}{j\omega L} + j\omega C\right) + 1} \cdot \frac{j\omega L}{j\omega L}$$

$$= \frac{R_1\left(j\omega\cfrac{L}{R_2} + 1 - \omega^2 LC\right)}{R_1\left(j\omega\cfrac{L}{R_2} + 1 - \omega^2 LC\right) + j\omega L}$$

If R_2 would be removed from the circuit then the term $j\omega\dfrac{L}{R_2}$ disappears from the expressions above. It is now easy to see where the resonant frequency must occur:

$$1 - \omega_r^2 LC = 0 => \omega_r = \frac{1}{\sqrt{LC}}$$

At resonant frequency the transfer function is

$$H(j\omega r) = \frac{R_1\left(j\cfrac{L}{R_2\sqrt{LC}} + 1 - 1\right)}{R_1\left(j\cfrac{L}{R_2\sqrt{LC}} + 1 - 1\right) + j\cfrac{L}{\sqrt{LC}}}$$

$$= \frac{\cfrac{R_1}{R_2}}{\cfrac{R_1}{R_2} + 1} = \frac{R_1}{R_1 + R_2}$$

What is really measured over the shunt resistor R_1 is the current I. So, the transfer function describes the admittance: $Y = \dfrac{I}{V_1}$. The impedance is thus: $Z = \dfrac{V_1}{I}$

The impedance at resonance (including the shunt re-

sistor) is $Z(\omega r) = \dfrac{R_1 + R_2}{R_1}$

The preferred method of engineers is to use the Bode Diagram. The Bode Diagram plots the magnitude and phase as follows:

$$A(dB) = 20 \log_{10}(H(j\omega))$$

$$A(\theta) = \tan^{-1}(H(j\omega))$$

The Bode Diagram [22] takes advantage of the asymptotic symmetry by using a logarithmic scale for frequency. It is more advantageous to plot H(s) logarithmically over large frequency spans. The logarithmic plot helps to maintain consistent resolution. Plots ranging from 10 Hz to 10 MHz can be displayed as a single plot if they are formatted logarithmically. **Figure 3** shows a typical response for a high voltage star connected winding. The frequency range of interest is between 20 Hz and 2 MHz.

Experience has shown that different sub-bands are dominated [23] by different internal components of the transformer and are subsequently more sensitive to different types of failures, as summarized in **Table 1**. Measurements above 2 MHz tend to be dominated by
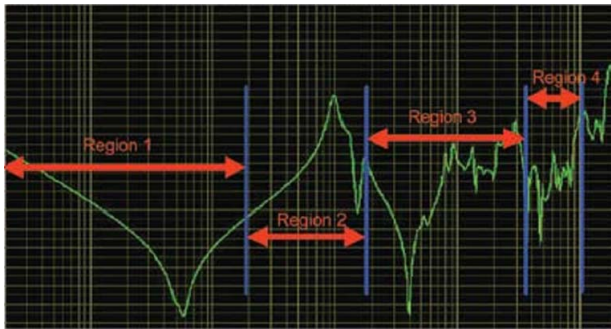
Figure 3. Frequency analysis bands.

Table 1. Frequency sub-band sensitivity.

Region	Frequency Sub-Band	Component	Failure Sensitivity
1.	<2 kHz	Main core bulk and winding inductance	Core deformation, open circuits, shorted turns and residual magnetism
2.	2 kHz to 20 kHz	Bulk component and shunt impedances	Bulk winding movement between windings and clamping structure
3.	20 kHz to 400 kHz	Main windings	Deformation within the main or top windings
4.	400 kHz to 1 MHz	Main windings, top windings and internal leads	Movement of the main & top winding, ground impedance variations

variations in grounding practices for test leads.

3. Measurement Procedure

The FRAX "Generator" (Gen.) generates (**Figure 4**) a sinusoidal voltage at a selected frequency and measures the input voltages, amplitude and phase, on two input channels "Reference" (Ref.) and "Measure" (Meas.). The instrument stores "Amplitude" and "Phase" data for both "Reference" channel and "Measure" channel as well as the ratio "Measure" divided by "Reference". The values can be plotted and exported as Magnitude, Phase, Impedance, Impedance-Phase, Admittance and more. The "Custom models" function makes it possible to calculate almost any parameter based on the measured/stored data. FRAX uses the sine correlation technique [24]. This means that the input voltages are multiplied by a sine and a cosine, and then averaged over an integer multiple of the interval of time. The sine, cosine and the voltage applied have exactly the same frequency. The sine correlation technique is well known and is suitable for Sweep Frequency Response Analysis (SFRA) measurements. Since the signals on the two input channels are treated the same way, the phase resolution between these two channels is very high. The rejection of DC offset and harmonics—referred to as the applied voltage—are in theory infinite. By increasing the integration cycles, the rejection gradually improves.

The IF Bandwidth is commonly used as a parameter defining the bandwidth around the applied signal analyzed. An IF bandwidth of 10% of the active frequency is equivalent to 12 cycles of integration. When considering SFRA measurements, winding measurements realistically consist of three categories. The winding categories are high-voltage, low-voltage, inter winding. (**Figures 5 -7**)

Figure 8 presents a high-voltage winding trace, a low-voltage winding trace and an inter-winding trace together from a common test specimen. This illustrates their general relationship.

4. Response Analysis

For the analysis of a measured response, the response in
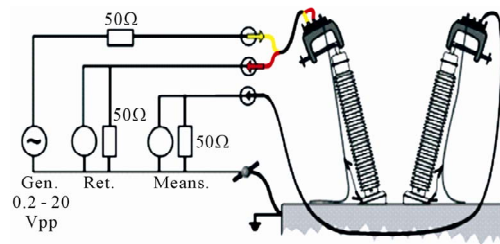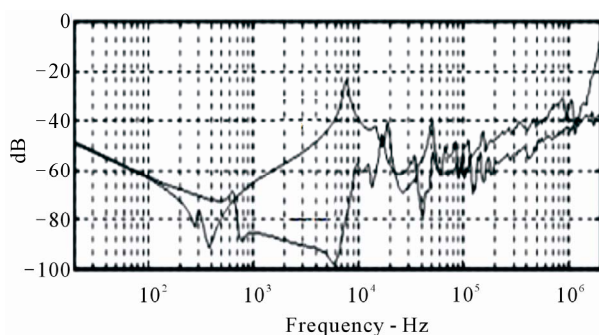

Figure 4. SFRA terminal connection.
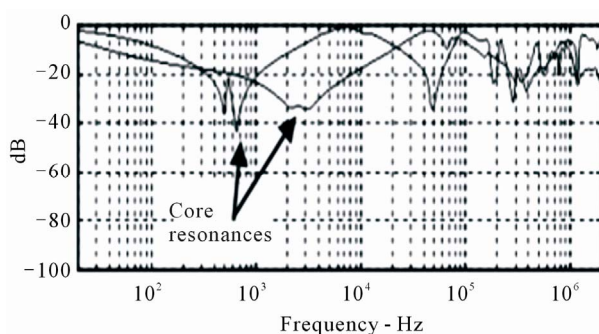
Figure 5. HV winding response.
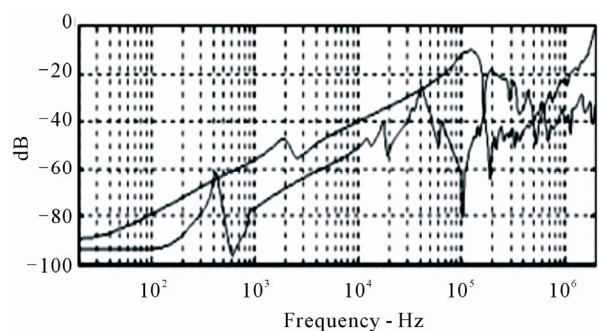

Figure 6. LV winding response.

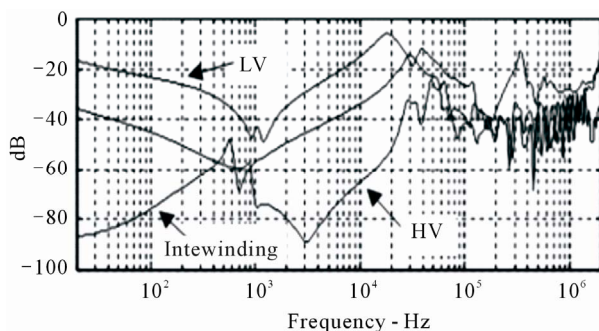**Figure 7. Inter winding response.**

Figure 8. Complete response.

compared with one of the following:

- An earlier result [25] for the same phase tested with the same tap changer position.

- If no earlier result is available then another phase [23] of the same transformer, tested at the same occasion.
- The same phase, same tap changer position but on a unit believed to be of the same design group and made at the same factory.

It is found that Cross Correlation [20] coefficient (CCF) is the most reliable statistical indicator to extract information from comparison method. The CCF is defined as:

$$CCF = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 * \sum(Y_i - \bar{Y})^2}} \qquad (2)$$

where X_i and are Y_i are the two series (or trace in the case of SFRA) being compared at each individual frequency 'i' and X-bar and Y-bar are the means. Equation (2) assumes two real series. In the case of signal processing the math becomes a little more involved, but the end results is still a coefficient between 1 and −1. In SFRA analysis negative CCF are not common but they do occur on occasion. Regardless, negative correlation coefficients are not considered acceptable when trying to look for deviations between traces.

Normalizing the results to the individual power spectrums is what allows this resulting waveform to be expressed in a simple single coefficient. **Table 2** helps provide a rough estimate of what the CCF means in simple language.

5. Fault Diagnosis

The following two case studies (**Table 3**) demonstrate two scenarios where SFRA response has been used to detect deformation or damage taken place in transformers.

Case 1: 41.67 MVA, 132/33 kV, 3φ Power Transformer at 132 kV Substation

The results here are from a three phase 25/41.67 MVA,

Table 2. Outcome of CCFs value.

Decision	CCF
Good match	0.95 – 1.0
Close match	0.90 – 0.94
Poor match	≤0.89
No or very poor match	≤0.0

Table 3. Case study of fault condition.

| Case	Capacity MVA	HT Voltage kV	LT Voltage kV	Year of manufacture
1	41.67	132	33	1998
2	14	33	11.6	1991

132/33 kV (vector group Dyn-1) power transformer manufactured by EMCO Transformers Ltd. (Maharastra, India) at 1998 for Bangladesh Power Development Board (BPDB) 132 kV sub-station. The transformer had tripped out of service on protection. No reference factory results were available for this unit. The phase-to-phase HV results didn't show typical variations from standard HV delta winding response. An overall look at the LV winding has showed several shifts between 200 kHz and 2 MHz. This is shown in **Figure 9** where it is clear that H3-H0 has consistently shifted at higher frequencies with respect to H2-H0 and H1-H0.

This is an indication of axial winding movement at X3 (Blue/C phase) phase. From CCF analysis method results (**Table 4**), this prediction can be more confirmed.

From the table, it is clearly visible that CCF values of phase A and phase B fulfill "Good Match" criteria in all 4 frequency sub-band regions. CCF values of phase C both with phase A or phase B meet up either "Good Match" or "Close Match" criteria in all bands except region 3. At region 3, both CCF values of phase C (0.7263 and 0.7681) drops down vigorously at "Poor Match" level.

Removing the transformer top cover, the active part was brought out and after a through physical inspection, the prediction became true with damage of LV (phase C) coil (**Figure 10**).

Case 2: 14 MVA, 33/11.6 kV, 3φ Power Transformer at 33 kV Substation
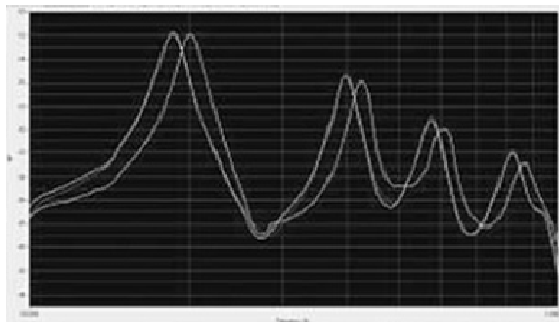
Figure 9. Close zoom of LV winding response (100 kHz - 1 MHz).

**Table 4. Test result of LV winding keeping HV open.**

Frequency Sub-band	CCF results		
	X1 - X0, X2 - X0	X2 - X0, X3 - X0	X3 - X0, X1 - X0
0 - 2 kHz	0.9981	0.9925	0.9954
2 kHz - 20 kHz	0.9943	0.9868	0.9736
20 kHz - 400 kHz	0.9853	0.7263	0.7681
400 kHz - 1 MHz	0.9892	0.9475	0.9424

The subjected transformer was running at Dhaka Power Distribution Company (DPDC). It is a 10/14 MVA, 33/11.6 kV (vector group - YNd11) power transformer manufactured by Brush Transformers Ltd. (Loughborough, England) at 1991. Due to its age of 20 years, frequency response of this transformer was taken to predict its aging effect. At first, test was carried on HV side keeping LV side open followed by LV side shorted. Corresponding Bode Plot response has been shown in **Figures 11** and **12**.
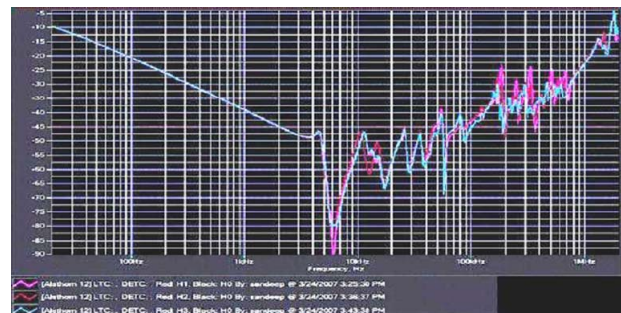
From the CCF result (**Tables 5** and **6**), it is easily viewable that the matching is very poor at low frequency region (0 - 2 kHz). This may be due to core deformation

Figure 10. Damaged LV (phase-C) coil.
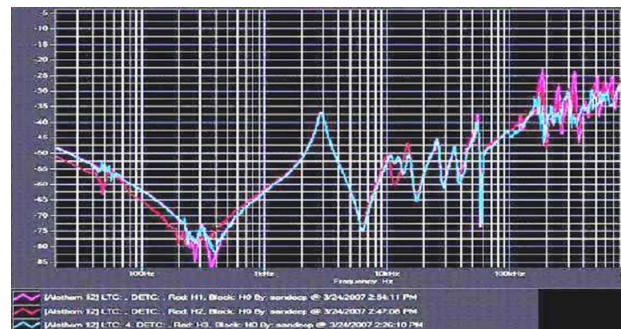
Figure 11. HV winding response (LV open).

Figure 12. HV winding response (LV short).

as a result of axial stress because the transformer is running for a long time (20 years). Again, poor matching at higher region (400 kHz - 1 MHz) indicates main coil deformation either by radial stress or by axial stress. This deformation is more severe for A phase (Red phase).

From LV winding response (**Figure 13**) and corresponding CCF calculation (**Table 7**), the previous assumption becomes stronger. Poor matching at low frequency region (0 - 2 kHz) and high frequency region (400 kHz - 1 MHz) again spans the prediction of core damage and main winding movement firmly. After replacing the transformer from the system, it was dissected and both the prediction became true

6. Conclusions

Sweep frequency response analysis method has been applied to a number of three phase and single phase

Table 5. CCF of HV winding keeping LV open.

Frequency Sub-band	CCF results		
	X1 - X0, X2 - X0	X2 - X0, X3 - X0	X3 - X0, X1 - X0
0 - 2 kHz	0.7981	0.7825	0.9914
2 kHz - 20 kHz	0.9743	0.9841	0.9736
20 kHz - 400 kHz	0.9523	0.9267	0.9081
400 kHz - 1 MHz	0.8394	0.8975	0.8427

Table 6. CCF of HV winding keeping LV short.

Frequency Sub-band	CCF results		
	X1 - X0, X2 - X0	X2 - X0, X3 - X0	X3 - X0, X1 - X0
0 - 2 kHz	0.9981	0.9925	0.9954
2 kHz - 20 kHz	0.9743	0.9861	0.9786
20 kHz - 400 kHz	0.9354	0.9283	0.9217
400 kHz - 1 MHz	0.8113	0.8671	0.8039
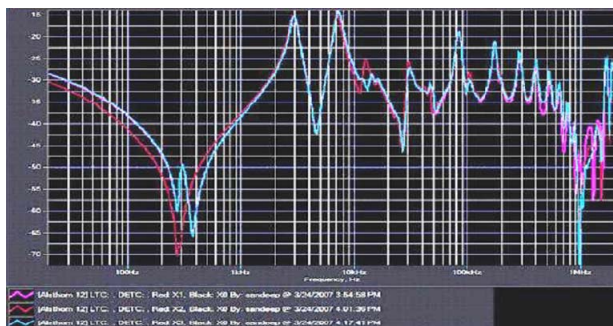
Figure 13. LV winding response (HV open).

Table 7. CCF of LV winding keeping HV open.

Frequency Sub-band	CCF results		
	X1 - X0, X2 - X0	X2 - X0, X3 - X0	X3 - X0, X1 - X0
0 - 2 kHz	0.8381	0.8325	0.9907
2 kHz - 20 kHz	0.9943	0.9921	0.9936
20 kHz - 400 kHz	0.9825	0.9867	0.9781
400 kHz - 1 MHz	0.8493	0.9275	0.8027

power transformers of different vector groups. This method is also applicable for mechanical deformation and damage diagnosis in distribution transformers. The parameter Cross Correlation Co-efficient (CCF) is found to vary significantly and consistently with mechanical displacements taken place in transformers. So it can be considered as the most effective indicator to predict the internal physical condition of the active part of a transformer.

7. Acknowledgements

8. References

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