Rahimpour, Hossein; Mitchell, Steve; Tusek, Joe "The application of sweep frequency response analysis for the online monitoring of power transformers". Originally published in the Proceedings of the Australasian Universities Power Engineering Conference (AUPEC2016) (Brisbane, Qld. 25-28 September, 2016) (2016)

Available from: http://dx.doi.org/10.1109/AUPEC.2016.7749347

The Application of Sweep Frequency Response Analysis for the Online Monitoring of Power Transformers

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Abstract— **Frequency response analysis (FRA) is a technique used to diagnose the mechanical integrity of a transformer winding; such diagnostic tools can be of enormous value since power transformers are a critical asset within any electrical network. To minimize the probability of an unexpected outage, or prevent a catastrophic failure, maintenance and monitoring of power transformers is essential for utilities. Over the past couple of decades, FRA has been utilized as an off-line diagnosis method. However, with the recent development in smart grid systems, there is now a growing interest in the development of on-line FRA techniques. This paper proposes a technique for in-service monitoring of power transformer winding deformation, which uses a broad frequency sine wave voltage excitation signal and high frequency Current Transformers (CT) in conjunction with the bushings test taps. Experiments using this system were conducted and then validated on a single-phase 22kV/110V voltage transformer.**

Index Terms—**Frequency Response, Power Transformers, Transformer Diagnosis, Online Monitoring, Bushing Tap Injection**

I. INTRODUCTION

Frequent monitoring of power transformers in power stations and substations is a preventive action to reduce the risk of in-service failures and outages. Conventional test methods are often unable to detect mechanical deformations of the windings, except in severe cases. Short circuit impedance testing gives information about the winding only at power frequency. FRA is a powerful tool, which gives comprehensive information on the winding mechanical structure and also the core and clamping structure. This is important as even slight winding deformation in the winding can develop into a failure of the transformer under fault conditions. Any changes in the active part of the transformer structure will cause relative changes in the internal inductive and capacitive network of the winding, resulting in changes in the frequency response of the transformer. A variety of methodologies have been developed to measure the frequency response of a transformer including Offline FRA, which has been widely used for commissioning and condition monitoring. However, the interpretation and assessment of the results remains of research interest due to the sensitivity of the test to many different parameters [1]-[4].

Online FRA has the potential to be an integral part of a smart grid asset management strategy. Cost minimization drivers in utility company's make desirable the replacement of time based routine maintenance with condition based monitoring using automated monitoring and interpretation. Online FRA has been a research topic over the past decade. In the early stages, development of online FRA focused on Impulse FRA (IFRA) with uncontrolled signals, which occur in nature like lightning or produced by switching in the power system. Since the frequency content of these signals is not controlled, it typically requires a significant time and effort to capture enough useful data for analysis.

Some of the researchers [5]-[9] favor the IFRA method using transients from the network or injected signals. To obtain the response curve from the signals the common signal-processing tools of Fast Fourier Transform (FFT) and Wavelet Transform (WT) are typically used.

A review of online FRA literature shows that in this application there has been little interest in using Sweep Frequency Response Analysis (SFRA) for in-service monitoring [10]-[13]. SFRA has the benefit of facilitating a better signal to noise ratio and can produce almost constant accuracy across the wide frequency range and there is a reduced need for complex signal processing. Therefore, development of SFRA for an online application could be of significant benefit to industry.

One of the challenges of in-service FRA is the need to have safe access to the measurement points and safe operation of equipment when the transformer is energized. In addition, the measurement scenario is one where the transformer is connected to the rest of the power grid (source, load, switches, etc.). Thus when determining the response, it is the response of the combined system that is measured and not just that of the transformer, which leads to complexity in interpretation.

To overcome the network's power frequency noise, measurements at high frequency are proposed, which have the potential to form part of a permanent monitoring system. Conducting the measurements through the bushing taps rather than the bushing terminals also makes it feasible and safer, for the staff performing the test.

To perform the measurements, high frequency Current Transformers (CT) are applied at the injection and measurement points. The signals are applied and measured through bushing tap couplers. In one configuration the bushing tap is used as a voltage divider with a constant ratio over a wide frequency band. Overall, this method provides for safe ground level access to perform in-service FRA.

II. Online Monitoring of Power Transformer

A. Methodology

Bushing tap injection techniques utilizing voltage sensors and current probes were considered by Setayeshmehr [10] and other researchers [11]-[13]. To date there has not been a practical solution or industrial application for the bushing tap injection method. The method proposed in this paper has the potential to form the basis of an in-service application. The non-invasive test arrangement will facilitate a permanent monitoring system on a power transformer which is sensitive to small changes in the insulation and winding condition. This is achieved by taking into account the influence of the connected network on the measured frequency responses. This includes the impact of capacitive coupling between the lines [14], reflections, transformer load and any change in tap position.

A very low voltage sine wave with a frequency range from 1kHz to 2MHz can be used as the stimulus. The reason for this bandwidth selection is to avoid the noise below 1kHz and the very high sensitivity above 2MHz associated with measuring leads and earthing techniques. For evaluating the results in this paper, this research will focus on the frequency band 100kHz to 1MHz which has been found to be the most useful frequency band for an online application.

B. Capacitive Bushing

Most high voltage power transformers have capacitive bushings with tapping points suitable for conventional Dielectric Dissipation Factor (DDF) measurements, Partial Discharge (PD) testing and bushing power factor monitoring. The tapping point also provides an access point for the online FRA signal injection or the corresponding measurement point for the response signal. The tapping point can be formed into a capacitive divider, which provides for a voltage reduction. Alternatively the point can be grounded to ensure that the voltage at the tapping point does not exceed limits during transients. It is the primary focus of this research that the tapping point be grounded when the transformer is in service.

To emulate a bushing on the 22kV/110V transformer for research purposes, a capacitive bushing model was developed, Fig. 1. The capacitive bushing model was constructed by considering the ratio of bushing C1 and C2 capacitance. The C1 capacitance which is the main capacitance of the bushing was chosen from typical bushing parameters to be 160pF and the bushing tap capacitance of C2 was selected to be 1600pF (ratio of 1:10). For a healthy bushing the ratio remains constant over a very wide frequency range and therefore can be used at higher frequencies to capture the frequency response of a transformer.

Figure 1. *Capacitive Bushing Model*

C. High Frequency Current Transformers

The research in this paper proposes the use of high frequency CTs around a supplementary conductor grounding the bushing tap. High frequency CTs are placed around the bushing tap earth on all capacitive bushings before putting the transformer into service. To measure winding responses, two CTs associated with two bushings are used, as an injection and measurement point.

Parameters of the two high frequency CTs used in this research are given in Table I. However, the parameters of the combined performance of CTs in the circuit depends on to be at injection or measurement points were different. Using the CT at the injection point returns the response given in Fig. 2 with the frequency band > 1kHz (-10dB). Using the same CT at the measurement point returns the response given in Fig. 3 with frequency band > 7kHz (6dB).

TABLE I. Parameters of High Frequency CT

Type	Transfer ratio at 50Ω	Primary window	Bandwidth at -3dB	Bandwidth at -6dB
CT1	1:10	15 mm	0.5 – 80 MHz	0.3 – 100 MHz

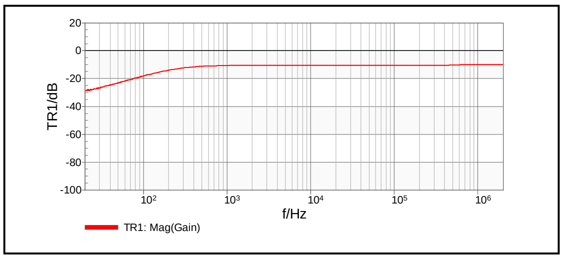

Figure 2. *Response of the injection CT*

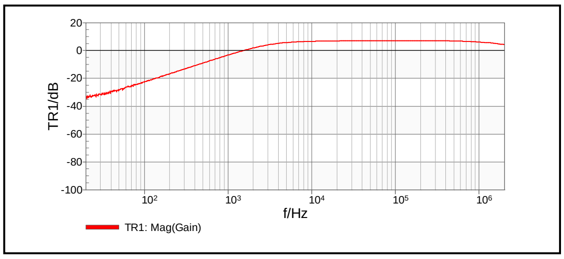

Figure 3. *Response of the measurement CT*

D. Test Object and experiments

A single phase 22kV/110V, 10VA voltage transformer was used to evaluate the feasibility of the proposed method, Fig. 4. The LV winding of this transformer was used as the test winding due to the number of resonance points appearing in the response. Capacitive bushing models were placed on the two LV terminals, to simulate the real bushings of a power transformer.

As the first step, the circuit was setup as shown in Fig. 5 (setup A) and the frequency response of the LV winding was measured on the bushing terminals. This is the most common way of performing an offline FRA in the factory and on site. The results for setup A are shown in red in Fig. 8.

The second step in the experiments was setup B as shown in Fig. 6, where the measurement was performed via the bushing taps. The signal was injected into the bushing tap at the bottom end of the winding and the response signal measured from the bushing tap at the top of the winding. The response of this measurement is shown as the green trace in Fig. 8.

Setup C in Fig. 7, measures the frequency response of the LV winding through the CTs and bushing taps, which is the proposed method for an online measurement. Transfer ratio of CTs is 1:10 and having 3 turns on the primary of the CT gives a ratio of 3:10. The signal was injected into the secondary of the first CT and the attenuated signal (by ratio of 10:3) goes through the associated bushing tap. At the measurement end, the response signal from the bushing tap is amplified by ratio of 3:10 to restore the amplitude for simpler comparison. As a default, the instrument measures the signal across a 50Ω resistance.

Fig. 9 shows the zoomed view of the responses in the frequency band 100kHz to 2MHz. When comparing the setup B response to the setup A response, the resonance points stayed the same at frequencies above 100 kHz but the anti-resonance points either moved or disappeared. There is also an approximately 13 dB drop in the magnitude of the response and this is due to the high impedance of the bushing tap, which is more dominant at lower frequencies.

When comparing the setup C response (CT plus bushing tap) to setup B response (bushing tap) on the frequency axis and above 100 kHz, the resonance and anti-resonance points stayed the same. There is also an approximately 33 dB (max) drop in the magnitude of the response and this is due to the extra impedance that the CTs and bushing taps introduced to the circuit.

However, for an online FRA measurement the baseline will be the measurement taken from the CTs through the bushing taps (Setup C). Any fault or change in the winding changes the response and the comparison of this against the baseline will be indicative of a fault.

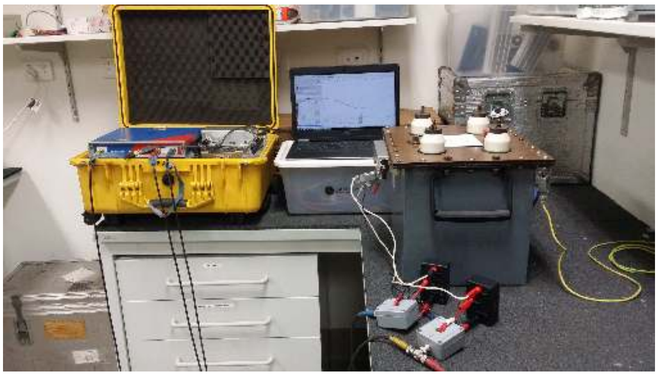

Figure 4. Experimental setup in the lab

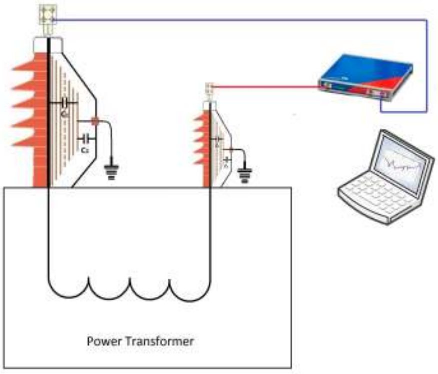

Figure 5. FRA measured on bushing terminals (Setup A)

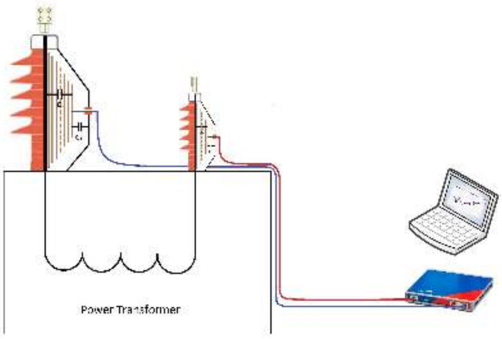

Figure 6. FRA measured on bushing taps (Setup B)

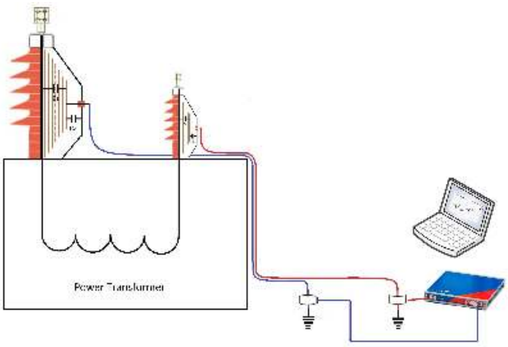

Figure 7. FRA measured through the CTs and bushing taps (Setup C)

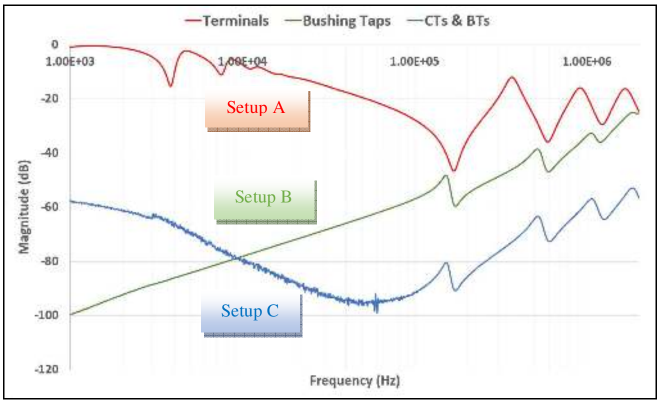

Figure 8. LV windng response of 22kV/110V transformer

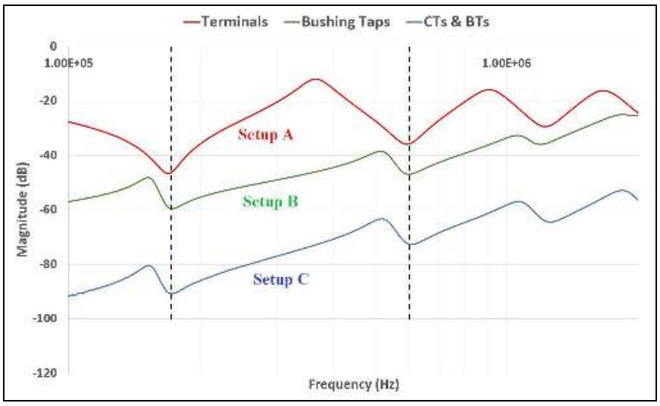

Figure 9. Zoomed responses from 100kHz to 2 MHz

E. Sensitivity of the response to load condition

To enable reproducible results, a good understanding of the sensitivity parameters associated with FRA are required. Since the measurements are performed at higher frequencies above 100kHz, the response won't be affected by core magnetization or demagnetization. In addition, this ensures the low frequency transformer and system noise does not affect the results.

Load condition influences are a concern for in-service FRA measurements. To investigate the effect of loads a series of experiments has been performed on a 22kV transformer under different load conditions. Resistive and inductive loads were applied to the secondary winding (HV) of the transformer and the changes to the responses investigated; the results are summarized in Table II.

TABLE II. EFFECT OF DIFFERENT LOAD CONDITION

Load	**330Ω**	**33Ω**	**48mH**
Impact on FRA	Negligible	Negligible	Negligible

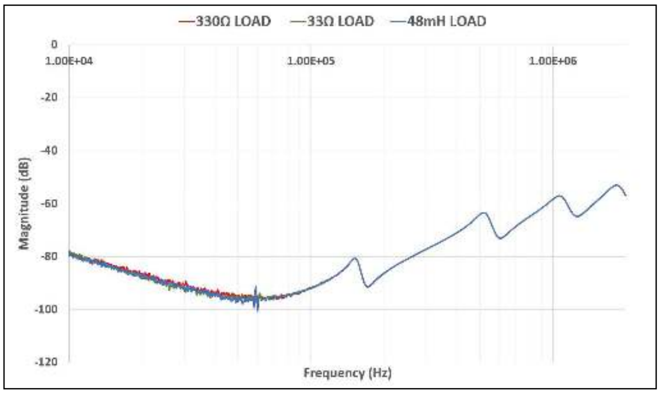

Figure 10. Load application impact on FRA

The load related impact on FRA has been experimentally investigated on the transformer used in this research and only slight changes in the FRA were detected in the frequency band of 100kHz to 2MHz.

F. Sensitivity of the response to input signal

Using the proposed setup C circuit, the excitation signal was injected into the first CT's secondary with the earthing strap passing through the CT core between the DDF point and earth. By increasing the number of turns of the lead through the core of the CT it was observed that the magnitude of the signal follows the number of turns. Fig. 11, shows the result of changing the number of turns from 3 to 9, showing good linearity.

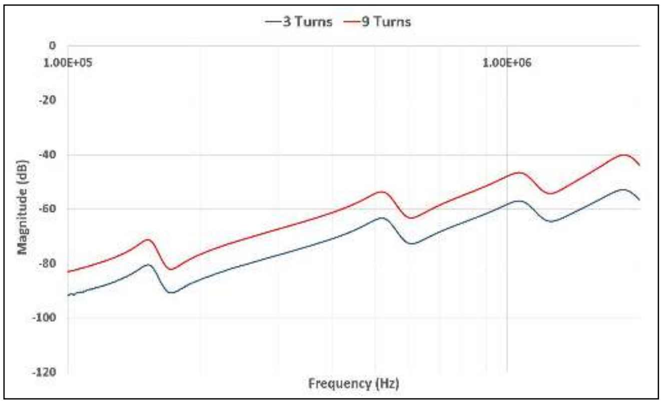

Figure 11. Input signal effect on FRA

G. Discussion

This research work focused on SFRA and its potential to become the preferred online monitoring tool for winding deformation and movement in power transformers.

Changes in the RLC network [15] of the transformer will affect the response and will be a part of the indications. A good knowledge of the factors that affect the frequency response is essential in the application of the method. Table III, lists some of the factors that can affect the response and Table IV and V lists some of the failure modes and the sub bands for detection [15]. As per the Table IV most mechanical failure modes are detectable in the recommended frequency band in this research.

When looking into the relationship of the FRA plot and the physical elements of a transformer, the sub band 3kHz – 200kHz shows a direct relationship with interactions between the windings. This means any change in the leakage inductance of the windings or in the parallel capacitance of the windings with respect to the core and its mutual couplings, will affect the response. The 200kHz – 1MHz band is sensitive to the series capacitances in the transformer RLC network.

TABLE III. FACTORS AFFECTING THE REPEATABILITY IN SUB-BANDS [15]

	3kHz – 200kHz	200kHz – 1MHz	1Mz – 2MHz
Temperature	✓	✓	
Moisture	✓	✓	
Tap Changer Position	✓	✓	✓
Tertiary winding	✓	✓	✓
Bushings		✓	✓
Measurement leads			✓
Oil level	✓	✓	✓

TABLE IV. MECHANICAL FAILURE MODE AND SUB BAND DETECTION [15]

	3kHz – 200kHz	200kHz – 1MHz	1Mz – 2MHz
Radial compression failure (Buckling in inner windings)	✓	✓	
Hoop tension failure (Buckling in outer windings)	✓	✓	
Tilt in conductors		✓	
Axial collapse (Telescoping failure)	✓	✓	
Break of clamping plates		✓	
Loose clamping		✓	
Spiral tightening	✓	✓	
Shifted regulating winding leads	✓	✓	✓
Distorted leads			✓

TABLE V. ELECTRICAL FAILURE MODE AND SUB BAND DETECTION [15]

	3kHz – 200kHz	200kHz – 1MHz	1Mz – 2MHz
Ungrounded electromagnetic screen		✓	✓
Multiple core grounding	✓		✓
Open circuit	✓	✓	✓
High impedance	✓	✓	✓

III. CONCLUSION

Offline FRA requires the transformer to be isolated from the network and an outage to be arranged and this imposes costs and risk on utilities. Online FRA helps with reducing the outage costs and having a permanent monitoring system on transformers ensures that the earliest possible indication of adverse winding conditions is identified. Sweep frequency response measurement through high frequency CTs using the bushing DDF points, has been shown in this paper to have the potential to be used for an online FRA measurement system.

To implement this method on an in-service power transformer some additional elements need to be added. For safe operation of the instrumentation and the safety of the personnel, a protection circuit and a filter for the power grid high voltage 50Hz component needs to be considered [13]. As an alternative to the 50Hz filter, an impedance could be placed in parallel with bushing tap to reduce the voltage level at the point of connection. To maintain signal quality a source with higher voltages will help to increase signal to noise ratio. Further research needs to be conducted on the proposed method to realize the system and ensure its robustness in the face of lighting and switching surges and for operation in outdoor environments, with continuous exposure to the elements.

ACKNOWLEDGMENT

The authors would like to thank Sam Murali and Geoff Bateman from Aurecon for their support and thank Aurecon for providing of test equipment.

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