SWEEP FREQUENCY RESPONSE ANALYSIS AS A DIAGNOSTIC TOOL TO DETECT TRANSFORMER MECHANICAL INTEGRITY

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ABSTRACT

This paper details the use of sweep frequency response as a diagnostic tool to detect winding deformation and core displacement in power transformers. Practical case studies are presented that demonstrates the effectiveness of this technique. Sweep Frequency Response Analysis has proven itself within eThekwini Electricity to be a valuable diagnostic tool for the detection of winding movement and other faults that affect the transformers impedance.

INTRODUCTION

The loss of mechanical integrity in the form of winding deformation and core displacement in power transformers can be attributed to the large electromechanical forces due to fault currents, winding shrinkage causing the release of the clamping pressure and during transformer transportation and relocation. These winding deformation and core displacement if not detected early will typically manifest into a dielectric or thermal fault. This type of fault is irreversible with the only remedy been rewinding of the phase or a complete replacement of the transformer. It is therefore imperative to check the mechanical integrity of aging transformers periodically and particularly after a short circuit event to provide early warning of impending failure. Hence an early warning detection technique of such a phenomena is essential. Frequency response analysis is recognized, as been the most sensitive diagnostic tool to detect even minor winding movement and core displacement.

BACKGROUND OF FREQUENCY RESPONSE ANALYSIS

Frequency Response Analysis has been developed over the years since it introduction in its 1960's. It initially used the impulse measurement technique and software was used to transform results from the time domain to frequency domain. In the 1970's Ontario Hydro pioneered frequency response by injecting a sinusoidal signal and measured the frequency response directly. In the 1980's National Grid Company (UK) refined the technique by first using the impulse method but soon the sweep method was employed as it was found to be better suited for site work and gave better high frequency results. The 1990's saw the introduction of the first commercially built systems to be used on site. Presently there are a number of worldwide users that use the sweep and impulse method.

ASSESSMENT OF MECHANICAL INTEGRITY

The traditional methods of electrical tests carried out on transformers such as winding capacitance, excitation current and leakage reactance measurements have proven to be not particularly sensitive to detect winding movement. Each of these methods has drawbacks.
Winding capacitance measurements can detect winding movement successfully only if reference data is available or if measurements can be made on each phase. In almost all older transformers, reference data is unavailable and on site per phase measurements are not possible.
The excitation current method is an excellent means of detecting turn-to-turn failure as a result of winding movement. However, if a turn-to-turn failure is absent, winding movement can remain undetected.
Per phase leakage reactance measurements generally shows little or no correlation between the phases. The three phase equivalent measurement is a broad test and can mask a variance in one of the phases. Further, the discrepancies from the nameplate value of 0,5 to 3 % can be a reason for concern. This makes accurate assessments of the mechanical integrity of the transformer very difficult.
Other condition monitoring tools such as dissolved gas analysis (DGA) do not aid in the detection of winding deformation and core displacement.

FUNDAMENTALS OF FREQUENCY RESPONSE ANALYSIS

The transformer is considered to be a complex network of RLC components. The contributions to this complex mesh of RLC circuit are from the resistance of the copper winding; inductance of winding coils and capacitance from the insulation layers between coils, between winding, between winding and core, between core and tank, between tank and winding, etc. However, a simplified equivalent circuit with lumped RLC components as illustrated in Figure 1 can be used to accurately explain the principle of frequency response.

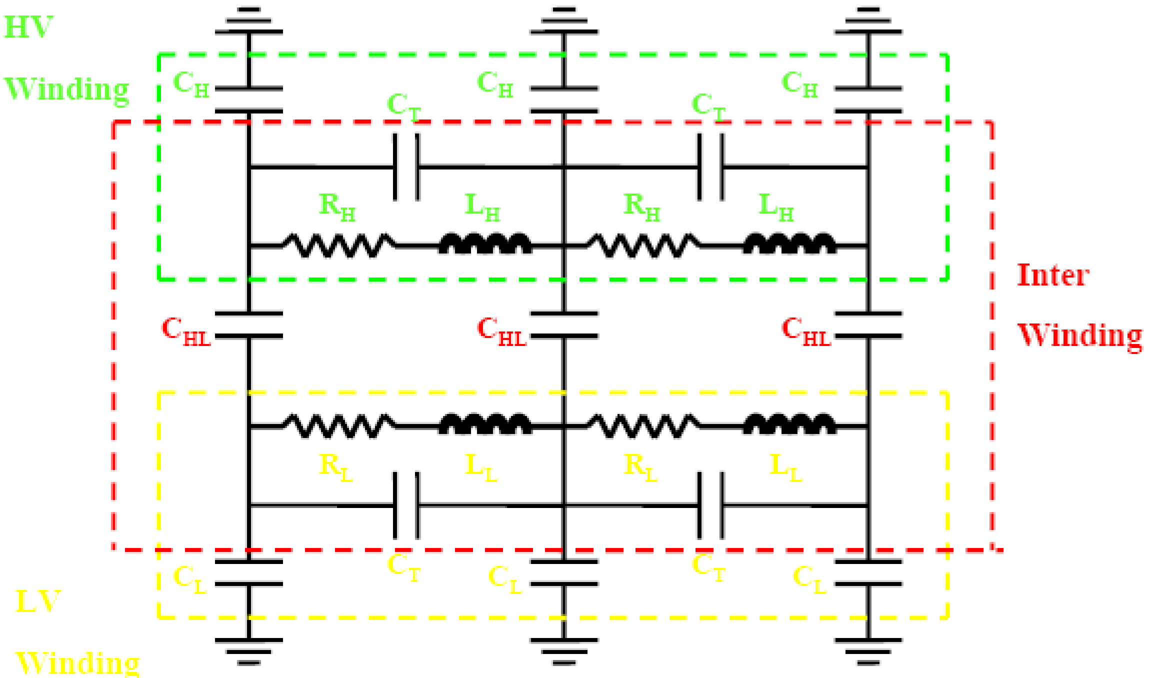


Figure 1: Simplified equivalent circuit with lumped RLC components

Any form of physical damage to the transformer results in the changes of this RLC network. These changes are what we are looking for and employ frequency response to highlight these small changes in the RLC network within the transformer. Frequency Response is performed by applying a low voltage signal of varying frequencies to the transformer windings and measuring both the input and output signals. The ratio of these two signals gives the required response. This ratio is called the transfer function of the transformer from which both the magnitude and phase can be obtained. For different frequencies the RLC network offers different impedance paths. Hence, the transfer function at each frequency is a measure of the effective impedance of the RLC network of the transformer. Any geometrical deformation changes the RLC network, which in turn changes the transfer function at different frequencies and hence highlights the area of concern.

INTERPRETATION OF RESPONSES

Measured responses are analyzed for any one of the following key indicators:

- Starting dB values (typically –30 to –50 dB for HV winding and –5 to –15 dB for the LV winding)
- The expected shape of a star and delta configuration with attention to the core resonant point/s.
- Comparison of response to fingerprint
- Comparison of response to the different phase of the same transformer
- Comparison of response from sister transformer
- Creation of new resonance frequencies and the elimination of existing resonance frequencies

A guideline for the use of the sweep method developed by Doble has been in existence for many years and has proven to be very useful in identifying the area of concern. These different frequency bands have different sensitivities to different mechanical failure modes.

Impedance at different frequencies relate to the resistance, capacitance and inductance of a transformer. The resistance is related to the physical construction of the winding (shorted turns, core earth etc.) and results in the vertical shift (dB axis) of the response. The capacitance and inductance are related to the geometry of the winding (deformation) and results in a horizontal shift or frequency shift.

Figure 2 below show the responses of a 132/11 kV, 30MVA, Yd, core formed, 3 phase, 3 limb transformer.

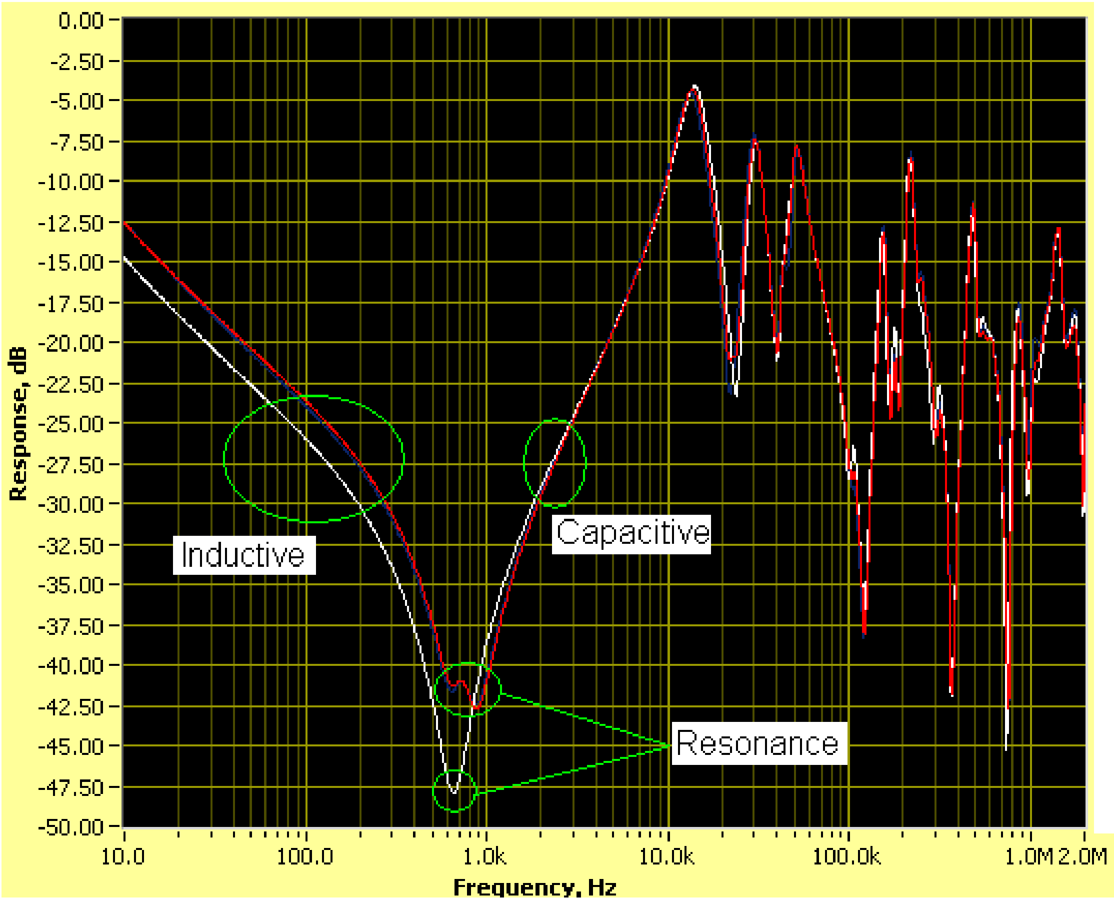


Figure 2: Frequency Response of a sound transformer

At the lower frequency range the capacitance of the transformer can be disregarded and the response is purely inductive. At these frequencies the inductance of the magnetic circuit dominates. There is a significant difference in the responses between the outer two phases and the center phase at this frequency range. This is due to the flux paths of the core. The center phase has two flux paths of equal reluctance and the outer phase has two flux paths of different reluctance. As a result the outer phases has two resonance points as compared to the center phase that has just one resonance point. This also accounts for the difference in the starting dB values.

At higher frequency ranges the response look very confusing and complex as a result of the numerous resonance points. At this frequency range the winding inductance dominates with the magnetic circuit effectively screened. Hence, the winding responses are less dependent on the magnetic circuit, which makes the measurement more sensitive to winding deformation. At the highest frequencies the inductance can be disregarded and the response is effectively capacitive.

ETHEKWINI ELECTRICITY'S EXPERIENCE

eThekwini Electricity is responsible for the maintenance of over 250 transformers operating at primary voltages between 275, 132 and 33 kV with ratings from 315 to 15 MVA. The average age of these transformers are twenty-five years old. Notwithstanding their age, these transformers have proven to be very reliable. Life assessment of these transformers takes into account oil analysis (oil screen and DGA), electrical and mechanical condition of the transformer. The availability of these tests results, allow asset managers to make informed decisions on the following actions:

- Replacement of the transformer before end of life
- Refurbishment of the transformer
- Carry out corrective maintenance
- Postponement of maintenance
- Loading of the transformer

For the above reasons, eThekwini Electricity has placed great emphasis on obtaining and understanding the condition of all transformers in the network, through the introduction of advanced diagnostic tools.
eThekwini Electricity's approach to condition assessment on transformers are as follows:

- Monthly visual inspection
- Oil analysis in the form of Oil screen, DGA, Furan analysis, Tan δ of oil at 90EC
- Electrical tests in the form of Tan δ and capacitance measurements on windings and bushings, 10 kV ratio measurements, excitation current measurements, leakage reactance measurements, Sweep Frequency Response Analysis (SFRA), insulation resistance measurements
- Infrared scanning
- Calculation of percentage moisture by dry weight and percentage saturation of oil.

SWEEP FREQUENCY RESPONSE ANALYSIS (SFRA)

Due to the lack of sensitivity of the existing test to detect winding movement and the positive response from international users, eThekwini Electricity introduced the SFRA (Doble M5100) as a diagnostic tool three years ago. Since its inception, the SFRA has proven to be a powerful tool for reliable and sensitive means of detecting winding movement and other faults that affect the impedance of the transformer.

As a standard eThekwini Electricity's performs SFRA measurements under the following conditions:

- On all new transformers for fingerprinting purposes
- As part of routine electrical tests
- After relocation
- After long duration short circuits
- After repairs to tapchanger
- After any vacuum treatment, purification and regeneration
- After any type of fault
- After any type of maintenance

SFRA measurements are done as a standard on the highest, lowest and nominal tap position. An additional measurement is made on the faulted tap position after any type of fault has occurred.

Short circuit tests on both the HV and LV windings are only performed on transformers that are suspected of having movement at high frequencies. This test method merely acts as an indication and does not identify the area of concern.

ENSURING RELIABLE MEASUREMENTS

SFRA like most test equipment requires correct and electrically sound connection to the transformer. Measurements must be made confidently and conscientiously to ensure reliable and meaningful measurements. In order to ensure meaningful measurements eThekwini Electricity has put into place a simple procedure that is followed for each test. Below are a few key points that must be followed to ensure meaningful measurements:

- The transformer under test must be completely disconnected from the network
- Neutral must be removed to ensure that the transformer under test is floating
- The transformer and tapchanger must be filled with oil
- All nameplate data must be accurately captured
- Check nameplate to ensure correct connections are made
- If DC testing was performed the core must be demagnetized before any SFRA measurements
- Prior to any measurements the leads must be tested
- Solid electrical connections must be made for the signal, measurement and earth lead.
- Measurements must be made at the lowest, nominal and highest tap position and the tapchanger movement must be from the lowest to highest. One additional measurement must be made on the tap position in which the fault occurred.

CASE STUDIES

These case studies illustrate real problems found with transformers in eThekwini Electricity's network.

Case 1: Shorted Turn Failure

Figure 3 (A): Response of the LV winding

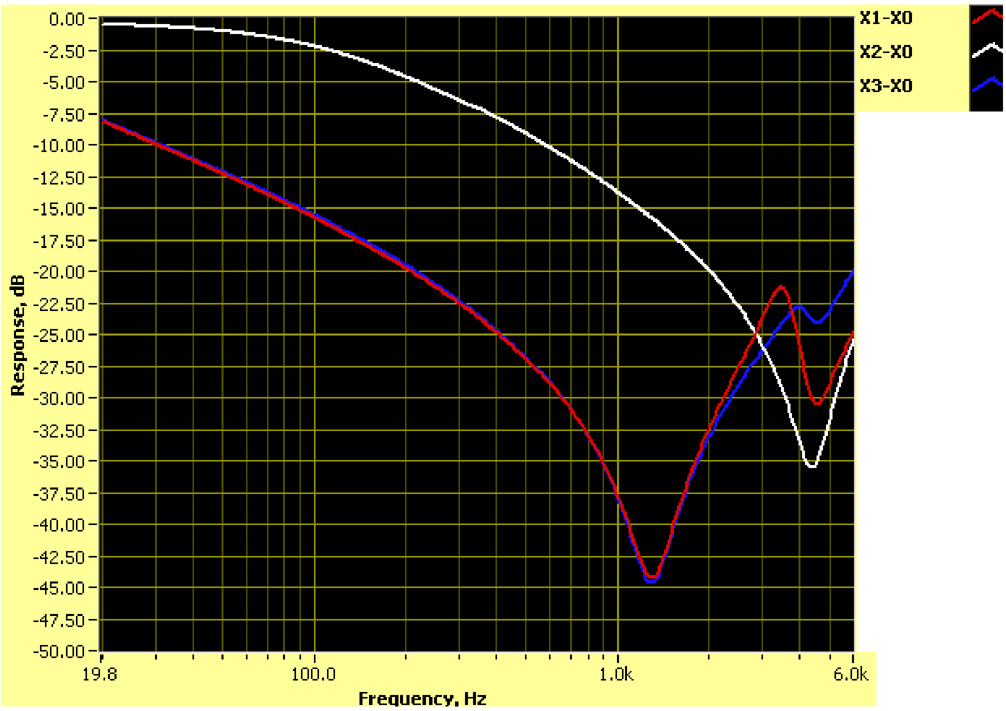
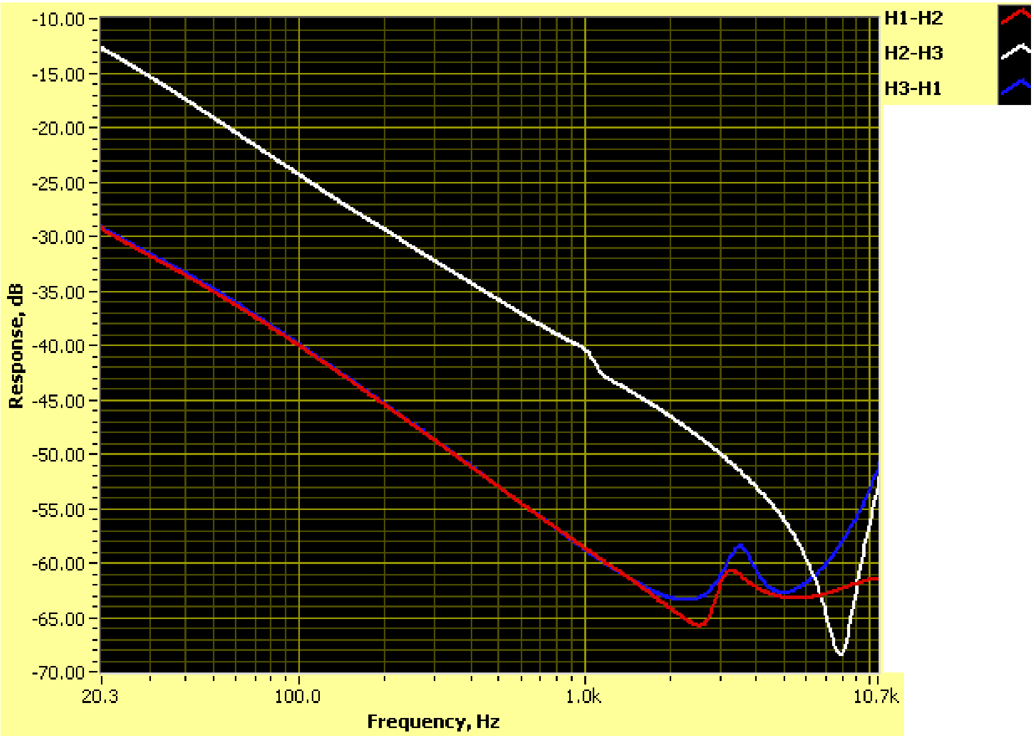


Figure 3 (B): Response of the HV winding



These are the responses of the HV and LV winding of the same transformer. There is clearly a significant difference in the White phase when compared to the other two phases. This is a result of a shorted turn failure. A shorted turn has the effect of creating an imbalance in the reluctance on one of the core limbs (in this case the white trace), which produces this characteristic change in the low frequency response. Excitation current and ratio test supported this diagnosis.

Case 2: Multiple grounded neutral

Figure 4 (A): Multiple grounded neutral (B): After repair

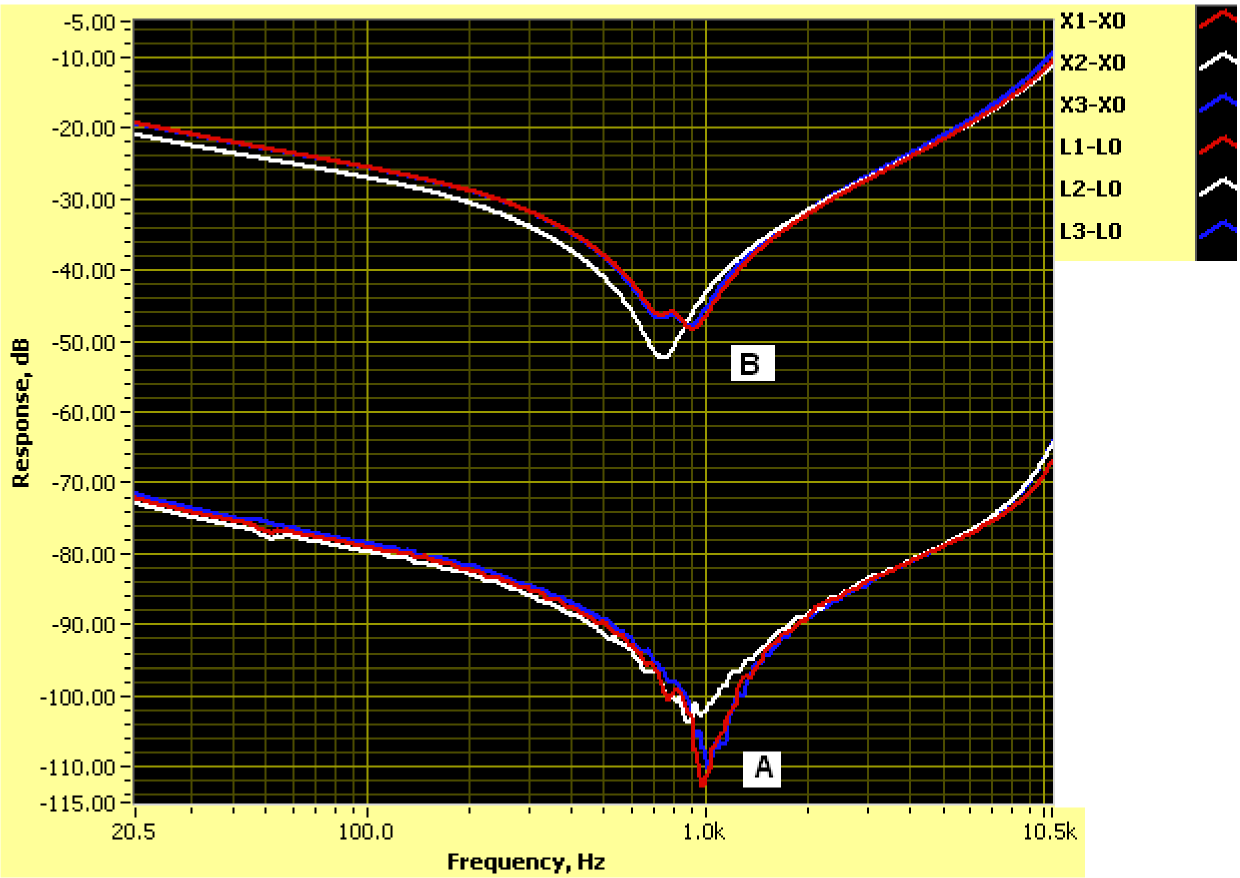


Figure 4 (A) shows the LV winding response of a multiple grounded neutral and Figure 4 (B) shows the response after the transformer was repaired. The comparison of the two responses shows a significant difference in the starting dB values. This difference in the dB or vertical shift in response A is attributed to the change in the resistance of the transformer under test.

Case 3: Core Magnetization

Figure 5 (A): Fingerprint response (B): Magnetized Core

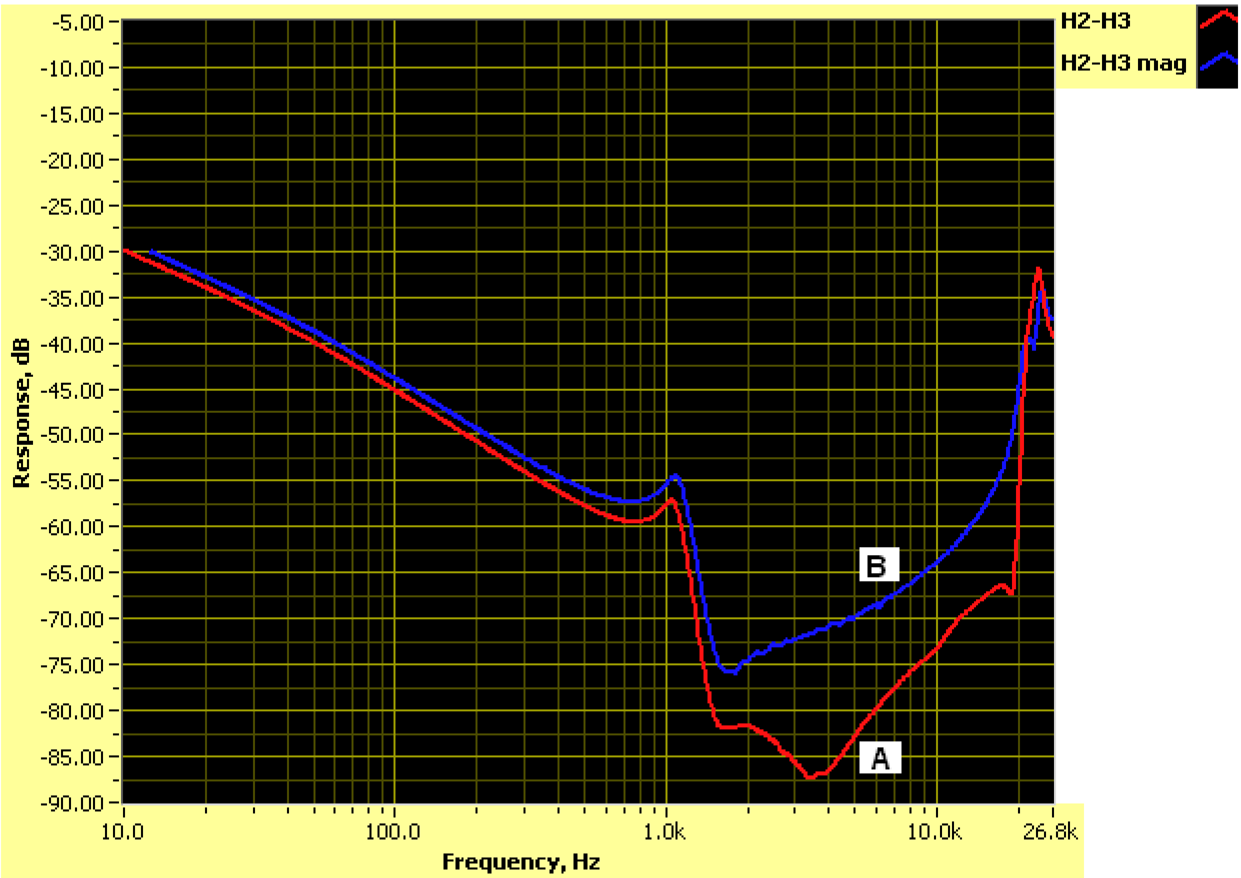


Figure 5 (A) shows the fingerprint response of the transformer and Figure 5 (B) shows the response as a result of a magnetized core. This transformer was taken out of service as a result of a tapchanger failure. The tapchanger was repaired and replaced. As a standard a micro-ohm test (DC test) was performed on the tapchanger contacts before returning the transformer to service. This DC test inadvertently magnetized the transformer core. The response of Figure 5 (B) shows a shift and the elimination of existing resonance frequencies. The transformer core was demagnetized and the new response matched that of the fingerprint.
This magnetized core situation was also identified by the excitation current test, which showed a significant increase in current from the fingerprint test.

Case 4: Extra Core Earth

Figure 6 (A): Responses of the middle phase

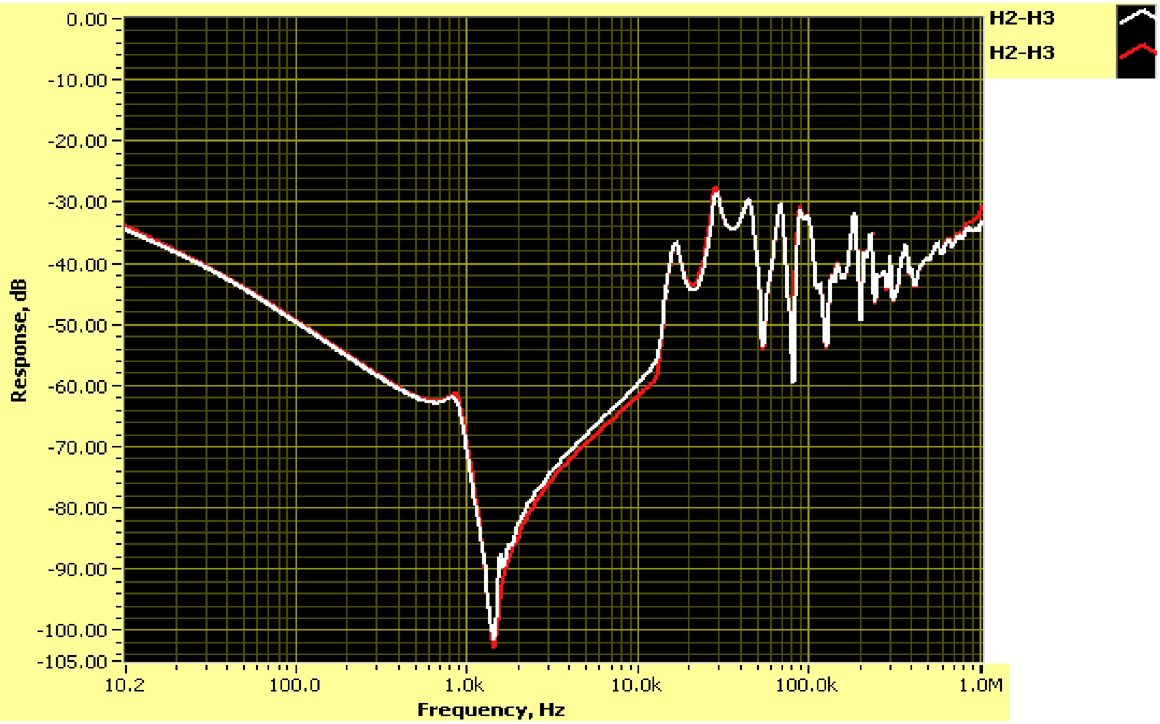


Figure 6 (B): Zoom-in of the above response

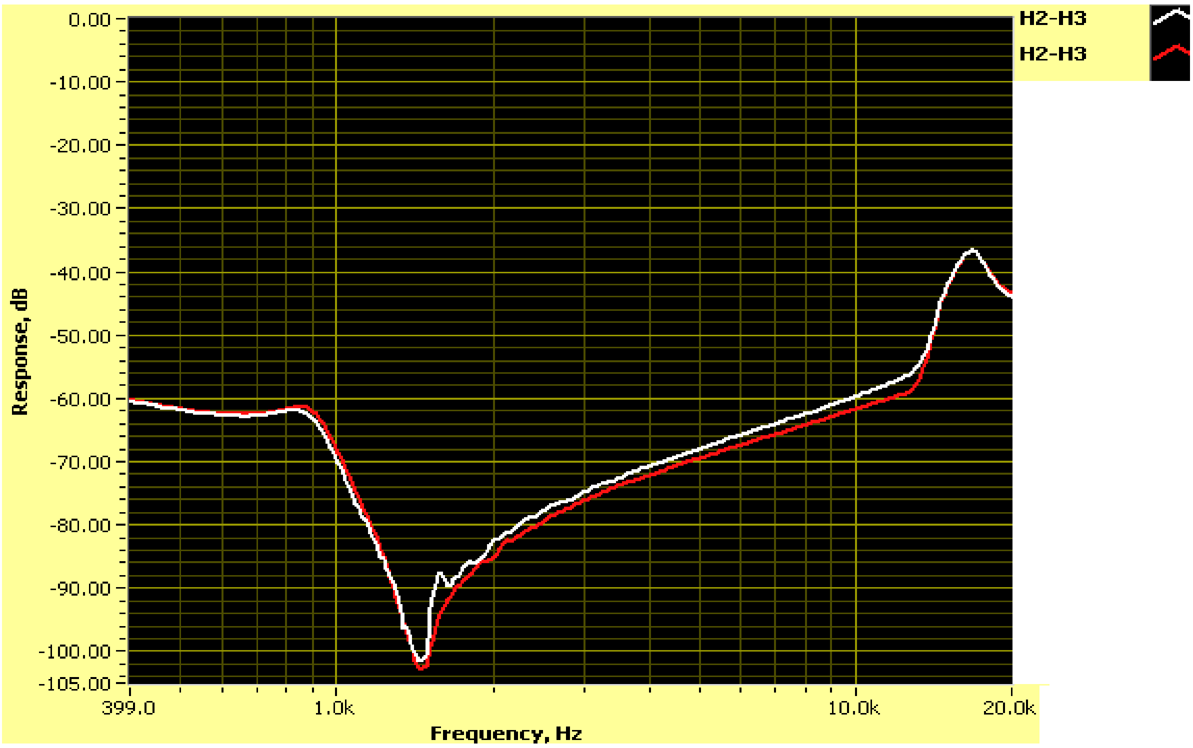


Figure 6 (A) and (B) shows the response of the middle phase with (White trace) and without (Red trace) the extra core earth. Differences were noted on all three phases but the greatest difference was noted on the middle phase. Figure 6 (B) shows a difference in the capacitance response from about 1,5 kHz to 14 kHz. Further, the White trace has a resonance frequency at 1,6 kHz which is absent in the Red trace. This creation of a new resonance frequency is clearly a cause of concern.

CONCLUSION

Sweep Frequency Response Analysis has proven itself within eThekwini Electricity to be a valuable diagnostic tool for the detection of winding movement and other faults that affect the transformers impedance. An advantage is that reference responses are not required to make an accurate decision as a comparison of response to the different phase of the same transformer and a comparison of response from sister transformer are used successfully to diagnose the mechanical integrity of the transformer.

The results obtained are reliable, repeatable and unaffected by test lead position, weather and electromagnetic interference. The test is easy to perform and operate, however measurements must be made confidently and conscientiously to ensure reliable and meaningful diagnosis. By focusing on its ability to detect winding movement we under emphasize the fact that measured responses are capable of providing an indication when no winding movement has occurred. This ensures that a transformer is returned to service quickly and avoids a costly internal inspection.

SFRA when used in conjunction with other diagnostic tools can provide a complete condition assessment of the transformer and in so doing ensure that informed decisions are made by asset managers.

ACKNOWLEDGEMENTS

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REFERENCES

1. Lapworth, J. A. and Noonan, T. J., "Mechanical Condition Assessment of Power Transformers Using Frequency Response Analysis," *Proceedings of the Sixty-Second Annual International Conference of Doble Clients,* 1995, Sec. 8-14.
2. Noonan, T. J. "Power Transformer Condition Assessment and Renewal, Frequency Response Analysis Update," *Proceedings of the Sixty-Fourth Annual International Conference of Doble Clients*, 1997, Sec. 8-5.
3. Lapworth J. A. and McGrail J. J. "Transformer Winding Movement Detection by Frequency Response Analysis (FRA)," *Proceedings of the Sixty-Sixth Annual International Conference of Doble Clients*, 1998, Sec. 8-14.
4. Dick, E. P. and Erven, C. C, "Transformer Diagnostic Testing by Frequency Response Analysis," IEEE Trans PAS-97, No. 6, pp 2144-2153, 1978.