

Transformer Frequency Response Analysis: An Introduction

Introduction

Frequency response analysis (FRA) is a well-understood technique in electrical testing. It is the ratio of an input voltage or current to an output voltage or current. Since the pioneering work of Dick and Erven at Ontario Hydro in the late 1970s, FRA has been applied to power transformers to investigate mechanical integrity. Experience has shown how to make measurements successfully in the field and how to interpret results. This article shows some typical results and how utilities are gaining benefit from what is, in fact, a simple test.

Frequency Response Analysis – FRA and SFRA

A standard definition of frequency response analysis (FRA) is the ratio of a steady sinusoidal output from a test object subject to a steady sinusoidal input. Sweeping through the frequency range of interest gives rise to the S in SFRA to distinguish it from impulse methods where the response is estimated rather than measured.

Figure 1 shows a simple two-coil arrangement subject to winding movement. The before and after SFRA traces are different, as shown in Figure 2.

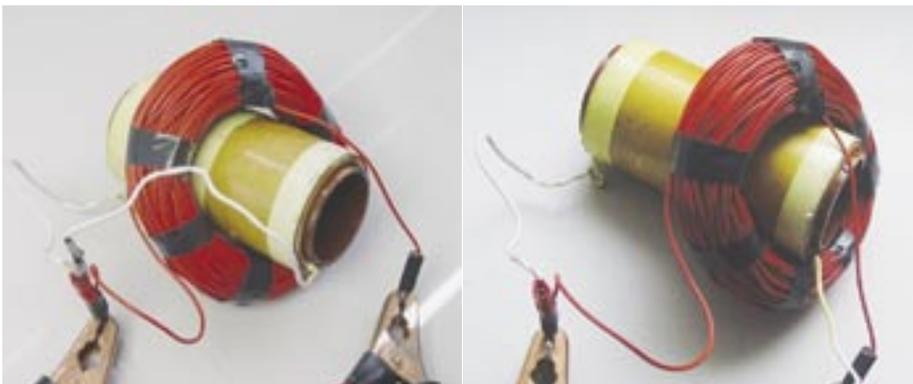


Figure 1 — Coil Movement



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The peaks and valleys of the traces are called resonances and correspond to combinations of capacitance and inductance within the coils. A change in resonance must be linked to a physical change in inductance or capacitance. Hence, we can deduce there has been a mechanical change in the windings.

But how do we use SFRA results in practice? The following examples are from real transformers. It is not always necessary to have reference results, although this is the ideal situation. Comparison with sister units or between phases is also possible. Phase-by-phase analysis is more complex and less reliable as windings are often asymmetrical through design and construction.

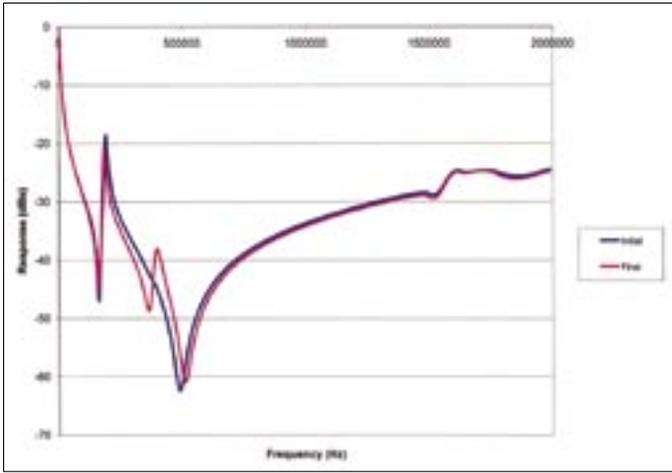


Figure 2 — Change in SFRA

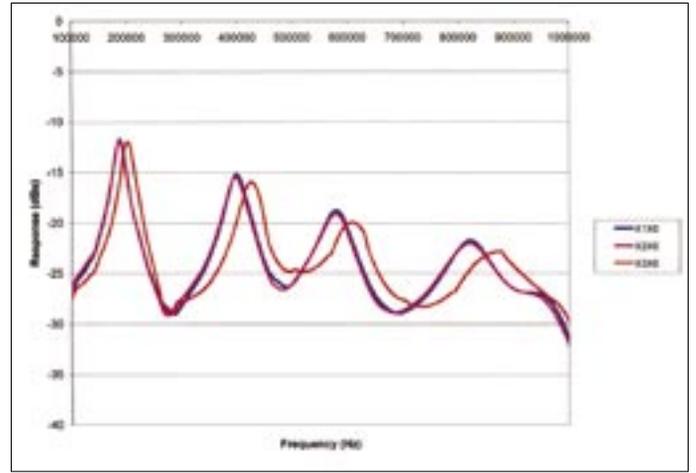


Figure 3 — LV Results for Partial Axial Collapse

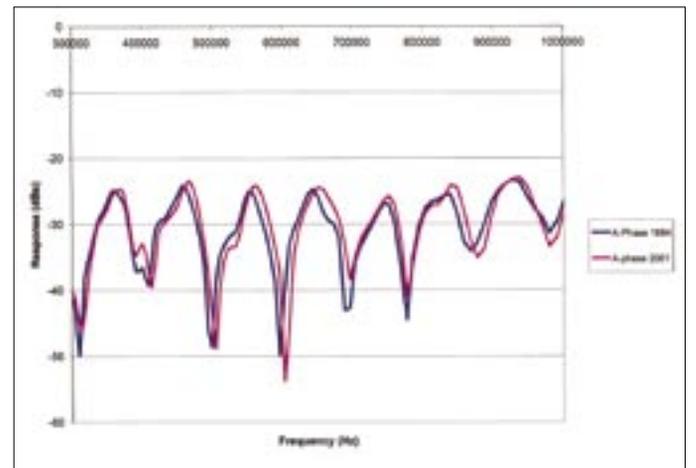
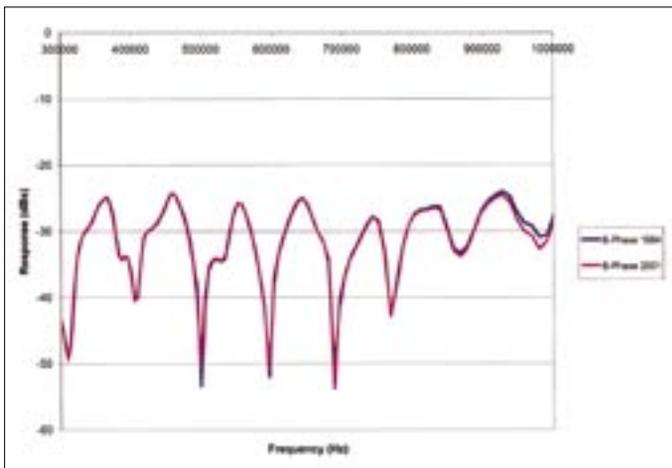


Figure 4 — Results for a Good Phase (left) and Bad Phase (right)

Practical Results – Axial Collapse of Winding

Axial collapse is also known as *telescoping*, where one winding shifts relative to the other like an expandable telescope. In this case a transformer tripped out on a fault pressure relay during a storm and three days after a previous dissolved gas analysis (DGA) test. The DGA showed a rise in acetylene from zero parts per million to 84 parts per million, indicating a major arc within the transformer. Other dissolved gases supported this diagnosis. Electrical testing included power factor, capacitance, winding resistance, excitation, and turns ratio. All gave acceptable results. SFRA, however, gave an indication of a partial collapse on one winding. The high voltage results gave no significant indication of a problem while the low voltage results were suspect, as shown in Figure 3.

Clearly, in Figure 3, the X3-X0 results (in red) show a shift to the right at a number of resonant frequencies. Natural asymmetry of the windings was ruled out as the high voltage results were acceptable and very similar. This result was similar to a case where another transformer had suffered a close-in fault, and subsequent SFRA traces revealed shifts to the right for just one phase. This would provide a reference set of results. Figure 4 shows SFRA results taken in 1994 and 2001. The good phases are very repeatable and indicate no significant problem. The bad phase shows clear and consistent shifts of resonances to higher frequencies.



The problem lies with their reduced ability to withstand further faults and the increased likelihood of catastrophic failure while in service. Figure 6 shows hoop buckling on one phase of a mobile transformer, as found during an inspection.

The SFRA response for this transformer showed a clear shift to lower frequencies for that phase, as shown in Figure 7. Previous results were available for a sister unit that showed the variation was not due to design or construction.

The diagnosis was made before the inspection, and the transformer returned to service during a peak load period with advice that it would be more likely to fail if it saw another nearby fault. The bad phase was re-wound some months later when the picture in Figure 6 was taken.



Figure 5 — Damage

Note that all results are between 300 kilohertz and one megahertz. A tear down of the transformer showed the damage in the B-phase, as shown in Figure 5, where the blocking can be seen to have collapsed under the winding.

Practical Results – Hoop Buckling of Winding

Hoop buckling, or winding compressive failure, is a common cause of deformation in transformers. The winding is bent but not broken. There are cases of transformers with severe hoop buckling remaining in service for several years. They have elevated DGA levels but otherwise perform almost normally.



Figure 6 — Hoop Buckling in Winding

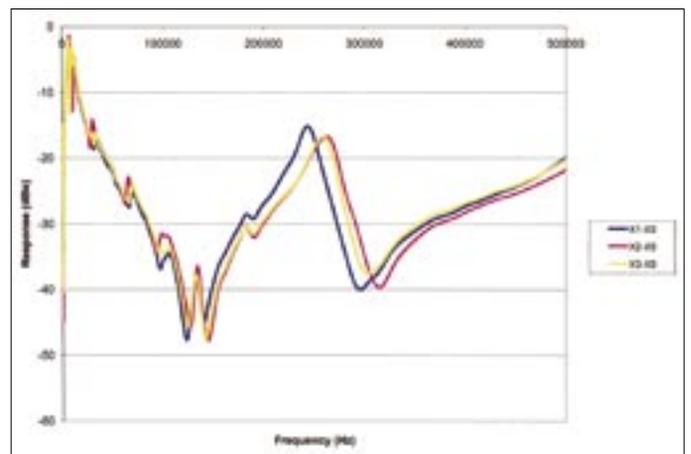


Figure 7 — Effect of Hoop Buckling on SFRA Results

Practical Results – No Change

One of the strengths of SFRA is in the power of a null result. When using a good repeatable test system, a null result, which shows no variation in the traces, is very strong evidence that the windings have not moved or deformed. Figure 8 shows five results for one phase of a generator step up (GSU) transformer taken over the course of eight years from July 1994 to July 2002. Clearly there has been no change in response, and the transformer is in unchanged condition. Small variations at low frequency relate to the state of core magnetization when the transformer was switched out of service, but it is clear that the main resonances have not changed.

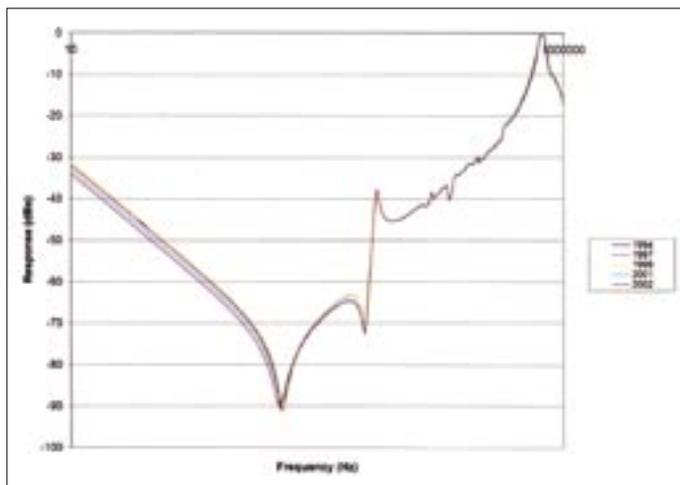


Figure 8 — Five SFRA Results Showing No Significant Variation

Interpretation

Experience has shown that the simplest form of interpretation of SFRA traces is with respect to a baseline. However, it is unlikely that we will ever get a baseline for all transformers on the electric supply network. Consequently, interpretation strategies which involve sister units or short circuit results are used. The least reliable method is phase-by-phase analysis, due to asymmetries brought in through construction and, for example, end mounted tap-changers. Automated approaches have been tried, but these produce both false positive results and false negative results. Simple difference analysis and correlation are sometimes useful as indicators but tend to show where the engineer should investigate the original traces (see McGrail and Sweetser). Doble Engineering is involved in the forefront of research into automated analyses that bring together differences, correlation, and manufacturer-specific experiences.

Key Features of SFRA in the Field

Practical experience has shown that SFRA measurements are simple to make, and a consistent measurement may be made in the field up to two megahertz (see McGrail and Lapworth). Above that frequency the value of the measurement is greatly limited by the variability of the test equipment and set up, especially with impulse systems, where it has been found that small movements in the leads will show great variation in responses (see Vandermaar).

The value in SFRA is the repeatability of results. Experience over many years has shown that a sweep system is the only way to extract that value from the results. The null result showing no movement in Figure 8 would be lost if the measurement were not repeatable to within +/- one dB. However, SFRA is only one tool and should be used in conjunction with other electrical and diagnostic tests to paint a complete picture of transformer health.

To investigate further, please visit the Doble website (www.doble.com) where further information may be found and examples and case studies are given. 

References

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2. Heathcote, M., *The J & P Transformer Handbook*, Newnes, London, 1998.
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5. Vandermaar, J., and Wang, M., "Key Factors Affecting FRA Measurements," IEEE Electrical Insulation Magazine, v. 20, n. 5, September/October, 2004.

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