

# **Sweep Frequency Response Analysis Transformer Applications**

## **A Technical Paper from Doble Engineering**

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### **Executive Summary**

This paper presents technical details regarding Sweep Frequency Response Analysis (SFRA) and the role it plays in transformer test and maintenance. SFRA is an electrical test that provides information relating to transformer mechanical integrity.

Details of the SFRA test method are given alongside practical results and case studies. For reasons of range, resolution and repeatability, the SFRA technique is shown to be superior to other frequency response techniques, providing results that may be used in key decisions by transformer engineers and asset managers.

The Doble M5100 is a robust and field proven instrument, which combines simple measurement techniques with powerful technical support from Doble Engineering.

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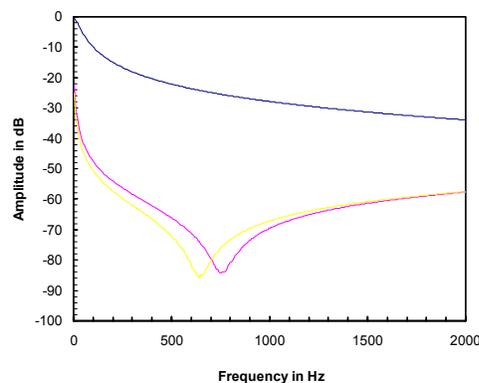
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## 1 What is SFRA?

Sweep Frequency Response Analysis (SFRA) is a tool that can give an indication of core or winding movement in transformers. This is done by performing a measurement, albeit a simple one, looking at how well a transformer winding transmits a low voltage signal that varies in frequency. Just how well a transformer does this is related to its impedance, the capacitive and inductive elements of which are intimately related to the physical construction of the transformer. Changes in frequency response as measured by SFRA techniques may indicate a physical change inside the transformer, the cause of which then needs to be identified and investigated.

Figure 1 gives an example where SFRA has diagnosed a shorted turn in a generator step up transformer. The SFRA results for each phase of the transformer are plotted as dB responses against frequency. In this case, the response of one phase is clearly very different from the other two, and the form of difference indicates a shorted turn in this case. It is important to get good resolution in results such as this to give clear and unambiguous traces at low frequencies



**Figure 1 Generator Transformer HV Tap 9 Shorted Turn on one Phase**

Details of SFRA testing procedures and typical examples are given in Chapter 6 “Case Studies” and in “ Appendix 1: Theory & SFRA Fundamentals”.

## **2 Power Transformers and Mechanical Integrity**

Power transformers are specified to withstand the mechanical forces arising from both shipping and subsequent in-service events, such as faults and lightning. Transportation damage can occur if the clamping and restraints are inadequate; such damage may lead to core and winding movement. The most severe in-service forces arise from system faults, and may be either axial or radial in nature. If the forces are excessive, radial buckling or axial deformation can occur. With a core form design the principal forces are radially directed, whereas in a shell form unit they are axially directed, and this difference is likely to influence the types of damage found.

Once a transformer has been damaged, even if only slightly, the ability to withstand further incidents or short circuits is 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. During a field inspection, the oil has to be drained and confined space entry rules apply. Since so little of the winding is visible, often little damage is seen other than displaced support blocks. 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 SFRA.

There is a direct relationship between the geometric configuration of the winding and core within a transformer and the distributed network of resistances, inductances, and capacitances that make it up. This RLC network can be identified by its frequency-dependent transfer function. Changes in the geometric configuration alter the impedance network, and in turn alter the transfer function. Changes in the transfer function will reveal a wide range of failure modes. SFRA allows detection of changes in the transfer function of individual windings within transformers and consequently indicate movement or distortion in core and windings of the transformer.

### **3 Motivation for SFRA Measurements**

There are two distinct environments for application of sweep frequency response measurement: in the factory and in the field. In both cases the procedures and precautions used to generate a good measurement are the same. However, there is a difference in motivation for the tests in each category.

#### **3.1 Factory Application**

Reasons to use SFRA in a factory environment include:

- Quality assurance
- Baseline reference
- Relocation and commissioning preparation

Manufacturers are using SFRA as part of their quality program to ensure transformer production is identical between units in a batch. The accuracy and repeatability of SFRA are key to the program; the range from 20 Hz to 2 MHz is required to diagnose variations related to the core, the clamping structure, windings and leads.

An SFRA baseline can be produced in the factory when the transformer has been filled with oil and dressed as part of the factory commissioning tests. Many customers now appreciate the benefits of having a good baseline for SFRA measurements in the field when they need to respond to an incident. These customers require an SFRA measurement as part of their transformer purchase specification.

There are cases where a transformer is also tested in the factory without oil immediately prior to transport to the customer site. Some utilities specify that the transformer is shipped with small test bushings fitted to allow this test to take place. This allows the transformer to be tested as soon as it arrives on site without costly dressing and oil processing procedures. SFRA is safe to perform on a suitably prepared transformer without oil as the test is low voltage one.

#### **3.2 Field Application**

Reasons to use SFRA in a field environment include:

- Relocation and commissioning validation
- Post incident: lightning, fault, short circuit, seismic event etc

Once a transformer arrives on site after relocation it may be tested immediately, without oil if required, for comparison with baseline references or with sister units. (The provision of small test bushings prior to shipping aids in testing). This gives confidence in the mechanical integrity of the unit prior to commissioning. Some utilities prefer to check the impact recorders after the relocation and then, assuming no adverse impact

recorder results are found, redo factory based SFRA tests once the transformer is dressed and ready for commissioning.

After a close up fault, or as a result of concern about the transformer from, for example, rising DGA levels, SFRA is a key tool in the engineer's toolbox for diagnosing the health of the transformer and its suitability for service. There is much to be gained in terms of information about mechanical integrity from an SFRA measurement, which supports evidence from Power Factor and Capacitance testing, Transformer Turns Ratio and Winding Resistance measurements.

Building a complete picture of the transformer from all available data is critical in making engineering judgements about an individual unit. Returning an unhealthy unit to service may prove catastrophic.

## 4 Which measurements are made?

The most useful SFRA measurement is the response of individual winding sections of the transformer at different frequencies. This allows problems to be associated with individual winding sections, rather than on a phase or winding generally. The SFRA does this in a simple way by injecting a signal of known frequency into one end of the winding and measuring the response at the other. By sweeping through the frequency range of interest, from just above DC to several MHz, it is possible to make accurate, repeatable and reliable measurements. SFRA measurements are independent of the lead arrangement and of the measuring device up through the frequencies of interest. For tests on a large power transformer 20m leads are needed which give reliable and repeatable results up to the MHz range.

Details of SFRA theory are given in “ Appendix 1: Theory & SFRA Fundamentals”.

An alternative method to SFRA to gain a measurement of the frequency response is to use an impulse method. This is discussed in detail in “Appendix 2: Frequency Response Analysis: Sweep v. Impulse”. It is Doble Engineering’s experience that, in practice, impulse methods are unreliable, lacking repeatability in the field and also suffering from poor resolution at low frequencies where vital information is contained about core and clamping structure integrity. Consequently Doble Engineering has produced a device which could be relied on in the field to support key decision making – using the Sweep Frequency approach.

To make an SFRA measurement, a transformer must be prepared as it would for power factor and capacitance measurements. Each winding section, HV and LV, is analyzed separately. Transfer function measurements, from HV to LV, may also be made, but these are less effective at detecting movement. Short circuit SFRA measurements, made for example by performing an SFRA on a HV winding with the LV winding shorted, provides further information about winding integrity and relates to transformer Leakage Reactance.

The SFRA provides a wealth of information in the form of a frequency response plot, which needs to be interpreted. Doble Engineering provides both a measurement and an interpretation service, relying on experts in the technique, and referencing a library of transformer SFRA results.

## 5 Frequently Asked Questions

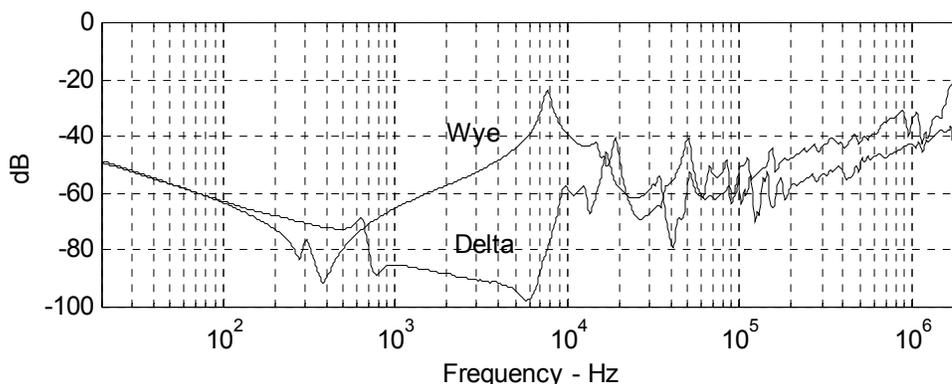
Over the years, Doble has built up a large database of results for transformers of many designs, manufacturers and vintages. We have also built up experience in the theory and practice of SFRA. This knowledge can be summarized in a series of questions that are frequently asked both at conferences and in the field.

### 5.1 What does an SFRA measurement look like?

An SFRA measurement, in simple terms, is a Bode plot, a measure of response against frequency. Response could be measured in Volts, but is usually measured in decibels (dB's) to relate the output to the input.

A typical response for two HV windings is shown in Figure 2.

High-voltage winding measurements have greatest attenuation as compared to the other categories. Most traces start between  $-30$  dB and  $-50$  dB and are initially inductive. High-voltage windings are much larger in overall size, which contributes to greater complexity in its distributive network. High-voltage winding measurements generally produce steeper resonances and more of them as compared to its low-voltage counterpart. Figure 2 illustrates these features.



**Figure 2 Typical HV Winding Responses**

The traces shown in Figure 2 are from different test specimens. Both traces are from 230 kV core-form transformers, however one trace is from a delta connected configuration and the other is from a wye connected configuration.

Typical results from a range of test windings are given in “Appendix 3: Measurements on Different Winding Types”

Data produced by Doble’s M5100 Sweep Frequency Response Analyzer is stored in a .csv format, which allows easy transfer between applications, and permits inclusion of data in standard report formats such as Microsoft Word™ or Excel™. Data is discussed in more detail in “Appendix 4: Data Collection and Display”.

## 5.2 What is the relation between FRA and SFRA?

FRA is the acronym for Frequency Response Analysis. To distinguish the Doble M5100 test set and the sweep method it uses from other techniques, we refer to SFRA where S stands for Sweep.

A brief history of FRA is given in “Appendix 5: SFRA History”.

## 5.3 Is it an easy measurement to make?

SFRA is a very easy measurement to perform. The transformer should be prepared as it would for a standard Doble power factor and capacitance test. The SFRA test requires a 3-lead approach, with the leads providing *signal*, *reference* and *test*. This approach means that the *signal* put into the test winding is measured to provide a *reference* which is then compared with the signal which emerges at the far end of the winding and is measured by the *test* lead. The three lead approach reduces the effect of the test set on the test results – making the measurement robust, repeatable and reliable.

To make the test leads easy to apply in the M5100, the *signal* and *reference* leads meet at a single connector clip; the test lead is connected by a similar clip. The clips are color coded to make application simple – red for *signal* and *reference*, black for *test*. Each test lead comes with a cable shield ground that needs to be connected to the transformer at the base of test bushings. This completes the test set up as a two port network, as described in “Appendix 1: Theory & SFRA Fundamentals”.

Figure 3 below shows typical test connection for a winding on a transformer. The Doble M5100 User Guide gives details of connections for most transformers found.

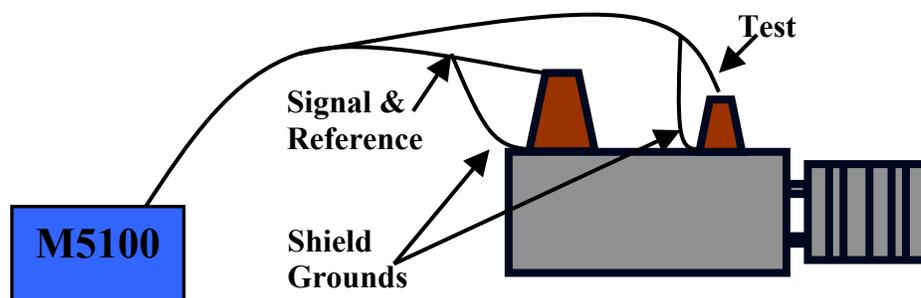


Figure 3 Typical Test Connections

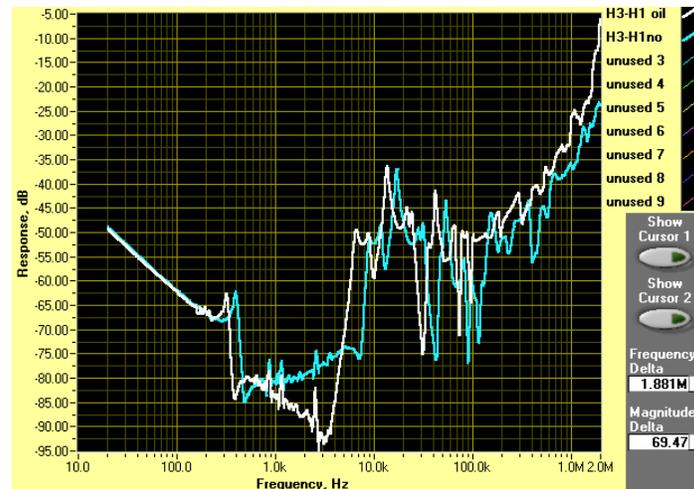
The importance of good connections and good test practices are discussed in detail in “Appendix 6: Test Issues and Precautions”.

## 5.4 Can we make measurements without oil in the transformer?

The short answer is: “YES!” SFRA is a low voltage technique and, *as long as suitable and relevant precautions are taken*, measurements can be made on a transformer without

oil. Clearly, any electrical test on a transformer filled with combustible gas is not recommended. Purging of gas with dry air and use of combustible gas monitors would be an appropriate first preparation step.

The effect of removing oil is to reduce the capacitance of the transformer, by changing a key dielectric from oil to air. This alters the position of the resonances and their amplitude. The result on a typical trace is to ‘stretch’ it to the right on the plot. Figure 4 below shows results from a 30MVA transformer tested with oil (“H3-H1 oil”) and without oil (“H3-H1 no”).



**Figure 4 Transformer tests with and without oil**

### **5.5 Has Doble been involved in international research?**

Doble has been involved in the development of SFRA as a practical tool for many years. By producing technical papers and through sharing field experience, Doble has been at the forefront of international research and provided a forum for development of the SFRA test for the electricity supply industry. Doble has also hosted comparison trials with other techniques for FRA measurement, such as impulse techniques, and shown the robust and superior nature of the SFRA in a variety of environments.

### **5.6 What are the bands and sub-bands shown in some results?**

The development of FRA was centered, in the late 1980's, on use of a Hewlett-Packard Network Analyzer. This had a restriction of only allowing 400 points per trace, which meant poor resolution at lower frequencies on a scan of 2 MHz. To account for this, several scans were done, the so called ‘sub-bands’ – 2 kHz, 20 kHz, 200 kHz, 2 MHz and 10 MHz. These sub-bands allowed analysis in detail across the frequency range. With a set step of 5 Hz in the 2 kHz band, the resolution never bettered 2.5%. The 10 MHz results were shown to be repeatable in a laboratory setting, but for field practicality results above 2 MHz are rarely used.

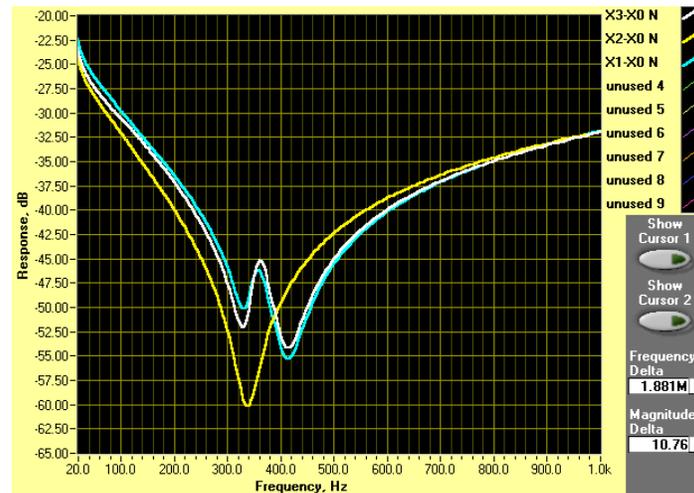
The Doble M5100 has a resolution that is logarithmic, remaining constant at 1.2% at every frequency. This means that resolution is maintained across the frequency range. The Doble M5100 software allows data to be displayed either in a log scale format or in a linear scale format.

The Doble M5100 software allows for display of the whole of the measurement made, or through an intuitive graphical interface allows particular sections to be viewed in detail. In addition the software displays sub-bands on a separate screen for those who are more comfortable viewing data in that way.

### 5.7 What causes variation in the 2 kHz range?

Low frequency responses when measuring across a winding with other windings floating and not shorted are strongly influenced by the core. This is an inductive region of the SFRA scan.

In a three-limb core form transformer, for example, there are two distinct magnetic paths available for the flux to travel. For a wye winding the A and C phases, which are the outer phases, see both paths which are reflected in the two resonance points at low frequencies in the scan. The center phase sees two similar paths. This results in a single resonance point. These variations between phases are illustrated in Figure 5 below.



**Figure 5 Low Frequency Variations Between the Phases of a Three Limb Core Form Transformer**

Clearly, the center phase, X2-X0, exhibits a single low frequency resonance, while the outer phases show two resonances.

The magnetic state of the core will affect results, much as is the case with transformer exciting current tests. The state of the core will be affected by both switching and by previous electrical tests performed on the transformer.

## **5.8 Is expert interpretation necessary?**

There is a learning curve associated with interpretation of SFRA traces. The traces need to be interpreted with experience, with reference to baseline results where possible, and with reference to manufacturer specific variations. Details of interpretation are given in Chapter 7 Interpretation.

As with many engineering sciences once the learning curve has been scaled, the need for expert support in interpretation depends on the situation. For most, after becoming familiar with the requirements, they are able to carry out the basic functions of gathering data and analyzing test results. Doble recognizes, however, the need for reference data and support in cases where an individual utility/organization has no reference data or expertise in-house of their own. Doble offers substantial support in this area, providing reporting capability and expert analysis of any transformer SFRA traces supplied by users in the field.

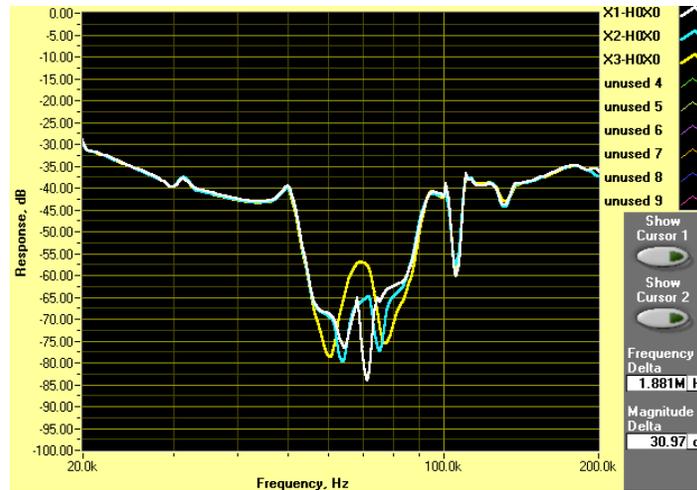
## **5.9 Can interpretation be automated?**

“Up to a point” is the only fair answer. “Appendix 7: Trace Comparisons” gives examples of comparisons between traces in basic terms using expert analysis.

Where baseline data is available, traces may be interpreted to look for degrees of difference. The main problem with this method is that small variations in one part for an SFRA trace may be more meaningful than larger variations in another part of the trace.

Test results form a picture in the form of a trace of response in dB against frequency in Hz or kHz – reducing that picture to a single number removes information from the picture and effectively hides what may be useful information. Difference plots and correlation calculations may provide some indication, but weighting these calculations for each transformer type and design has not yet been achieved in practice.

Baseline results may not always be available for a particular transformer. Here reference may be made to sister units or to transformers from the same manufacturer. Individual manufacturers may have variations that are specific to their transformers. Figure 6 shows the SFRA results for a 560 MVA 345 kV transformer in one section of the frequency range. Clearly there are differences in the 60 kHz to 90 kHz range. The question is – “Does this imply winding or core movement?”



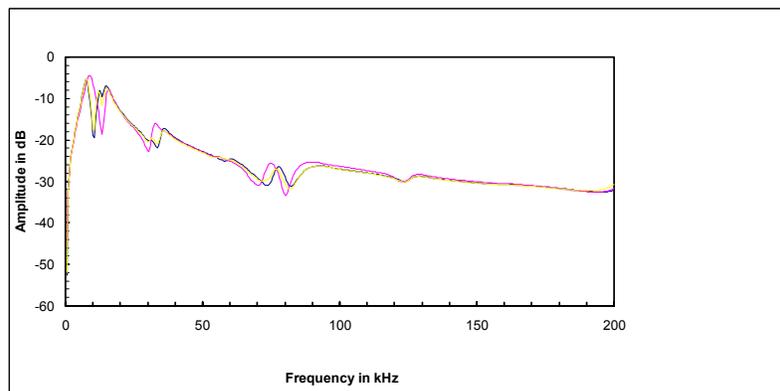
**Figure 6 Questionable Results**

The answer in this case is “NO!”

The reasons are simple:

- The traces are highly consistent between phases over the rest of the frequency range
- Other transformers from this manufacturer show similar variation in a similar frequency range

Figure 7 below shows data taken using an HP system some years previously on a transformer from the same manufacturer, but different kV and different MVA. The transformer is a spare but is known to be in good condition. The traces from three phases of the transformer overlay very well – here using Microsoft Excel™. There are also differences in the 60 kHz to 90 kHz region, which are similar to those found in the questionable results. Consequently we can say that the differences in the questionable transformer are not unexpected, and should not be interpreted as indication of winding movement. This type of interpretation requires experience with the test and a good understanding of how to interpret test results.



## **Figure 7 Results from same manufacturer**

### **5.10 Are reference results necessary?**

Reference results are preferred but not essential. Results from a sister unit from the same manufacturer may serve in their stead. Several examples of internal winding movement and related failure being detected by SFRA are available where diagnosis was made without use of reference results. The discussion in the Section 5.9 is a good indication of an interpretation made without direct reference results but with a knowledge of the variations produced by individual manufacturers.

The best way to obtain reference results is on completion of the manufacturing process. This can be done while the transformer is still in the factory and is undergoing commissioning tests that require the transformer be in a state which is identical to that when it is used in the field.

### **5.11 Do we have to disconnect all the bus work?**

Ideally, yes. This way the transformer will be in identical states each time it is tested.

The Doble User Guide gives details of connections, which should be made for a variety of transformer designs.

However, there are cases where it is impractical or infeasible to remove short lengths of bus bar from a transformer. In these cases the test may be performed with short lengths attached; the results will be affected by the nature of the bar, its inductance or capacitance, and may negate the possibility of comparing results with sister transformers.

Connection of long lengths of bus bar, as may be found in a generator station on a GSU LV winding is not recommended. The test may be performed in this condition, but the results may vary substantially from those without the bar attached. Typically, at generator stations, SFRA is incorporated into the transformer maintenance and assessment work at outage time. The transformer is then disconnected for a range of tests.

## 6 Case Studies

The examples given here are from power transformers, tested in the field in response to an incident, or as a part of routine assessment. Examples of responses from different windings are given as examples in “Appendix 3: Measurements on Different Winding Types”.

Trace comparison is the primary method for the analysis of SFRA results. Comparisons can be made against the baselines and previous data, sister unit results, and phases. Assuming the test equipment provides reliable and repeatable results, the initial expectation is that any data comparison should result in near perfect overlays.

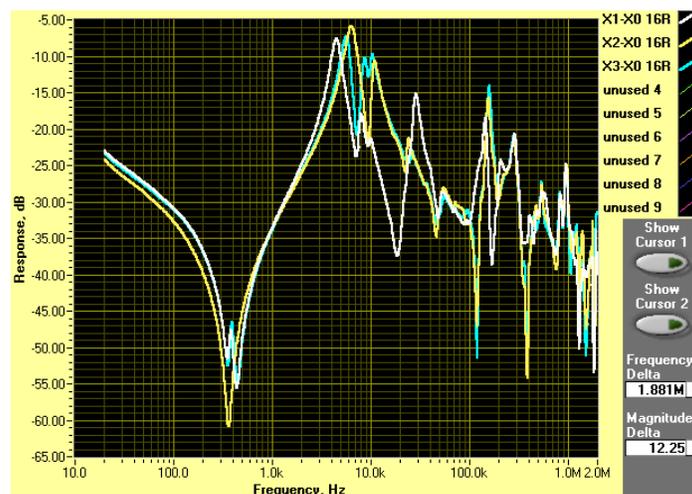
The Doble database indicates that various levels of expected comparison exist. The level of comparability expected may be categorized in three ways. These are shown and discussed in “Appendix 7: Trace Comparisons”.

### 6.1 Case Study 1: After an Incident

A 30/40/50 MVA transformer was subject to over current when a generator was switched in behind it out of phase. It was carrying 36 MVA at the time of the incident, the generator remained in service for 5 minutes, and the transformer remained in service for a two more hours. The transformer was tripped manually.

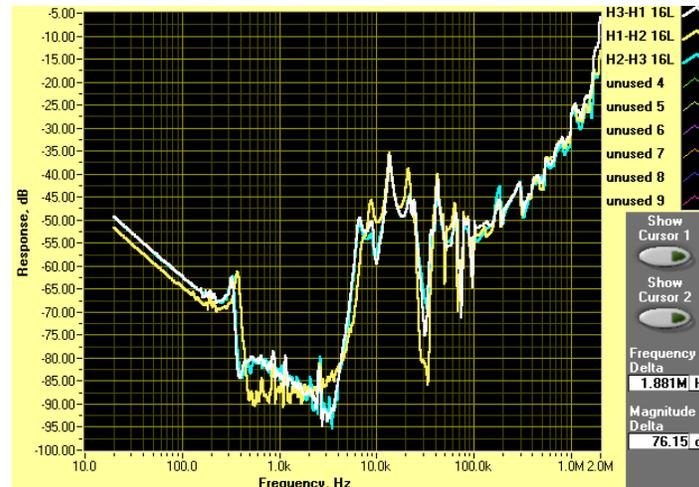
Figure 8 shows the LV winding traces using the Doble M5100 device.

There were no good reference results for this transformer available. It was clear from the results, however, that the A phase (marked as X1-X0) is substantially different over a range of frequencies – new resonances, shifted resonances and amplitude differences. This was a clear indication, without resort to reference traces, of probable movement or distortion on this phase of the transformer on the LV winding.



**Figure 8 LV SFRA Traces after Incident**

The HV SFRA traces are given in Figure 9. These show variations that are commonly found in HV delta windings – as described in “Appendix 3: Measurements on Different Winding Types”.

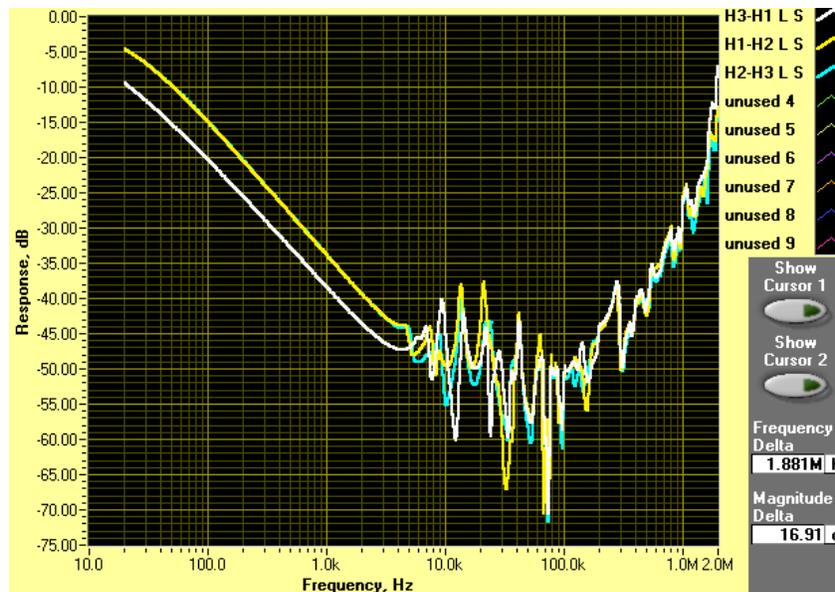


**Figure 9 HV SFRA Traces after Incident**

The results are an indication that there is unlikely to be any substantial movement or distortion on the HV windings. Variations on the B phase, H1-H2, follow normal patterns at lower frequencies for a delta winding.

The LV and HV traces, when taken together, show that there is likely to be winding movement or distortion and that it is concentrated in the LV winding on one phase.

Support data was generated by making HV measurements while shorting across the LV bushings. This short circuit SFRA test requires good resolution at low frequencies as this is where the major diagnostics take place for this test. By shorting out the LV windings, the measurement is made with almost no reference to the core at the lower inductive frequencies of the SFRA measurement. The windings on the transformer are thus tested without interference from the core. The responses should overlay perfectly up to about 2 kHz.



**Figure 10 Short Circuit SFRA test of HV windings**

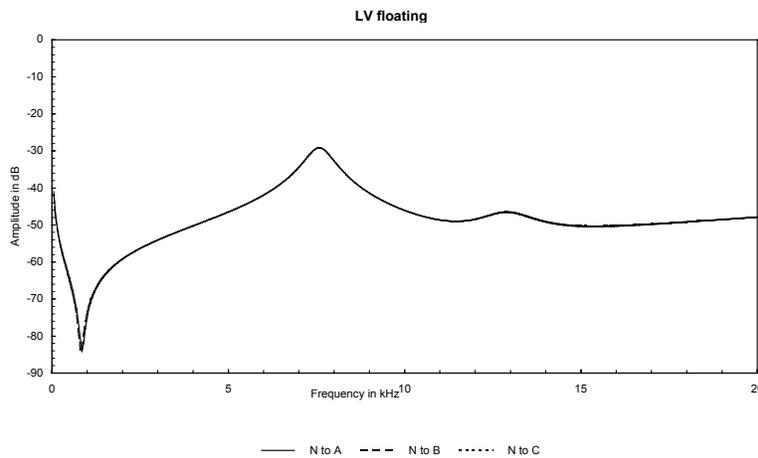
It is clear from Figure 10 that two phases, the B (H1-H2) and C (H2-H3) phases overlay perfectly at low frequency. However, the A phase (H3-H1) diverges somewhat. This is strong evidence of winding movement or deformation on this phase as the low frequency response, as has been noted, is almost independent of the core. An alternative explanation is that the A phase is OK, and the other two have shifted, but for this to be true they would have to have been moved or distorted in identical ways to have such similar responses.

The transformer was removed from service and inspected internally. This revealed a break in one lead within the tap changer; this problem had not been identified using power factor and capacitance, winding resistance or transformer turns ratio tests. Leakage reactance, which relates to SFRA results at 60Hz, also showed the problem.

## 6.2 Case Study 2: Assessment and Relocation of a GSU

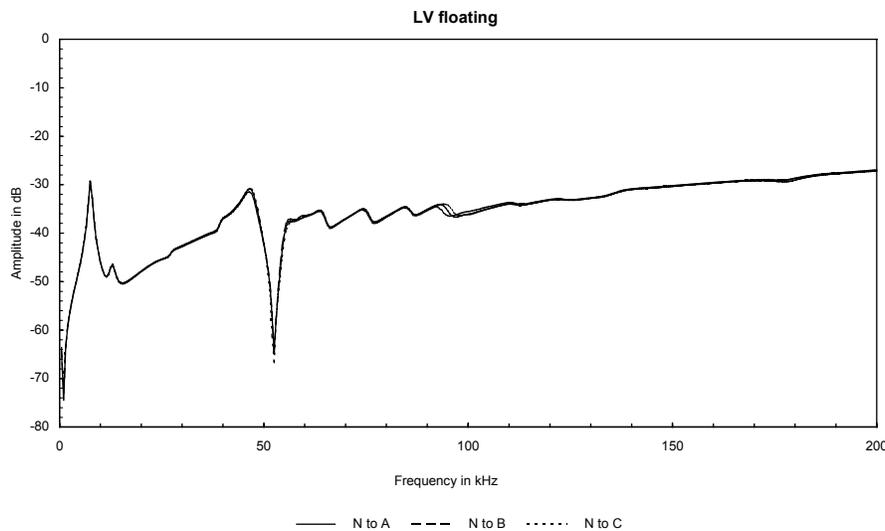
A generator station in the UK suffered a failure on a large Generator Step Up (GSU) transformer after a fault. A replacement was identified at another generator station. As part of the suite of electrical tests used to assess the replacement unit, SFRA was performed; this provided both a check on the mechanical integrity of the unit and provided a baseline for comparison after the relocation of the unit.

The transformer was SFRA tested at neutral tap and at one extreme tap position. Results here are for that position. Figure 11 shows the 20 kHz sub-band for the transformer – all three phases are present and overlay very well.



**Figure 11 SFRA 20kHz Sub-band Scan Before Relocation**

Figure 12 below shows the results for the 200 kHz sub-band.

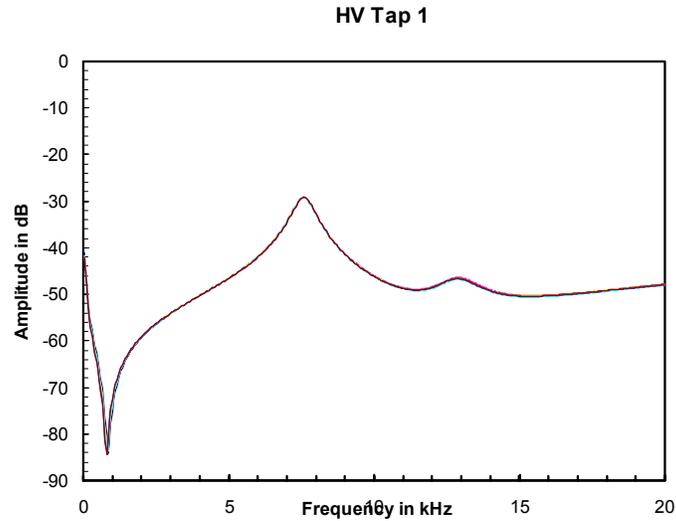


**Figure 12 SFRA 2kHz Sub-band Scan Before Relocation**

Once again, all three phases are present and overlay well. Slight differences between the phases at around 100 kHz may be attributable to design, as such variations occur in similar transformers, as described in Section 5.9 “Can interpretation be automated?”

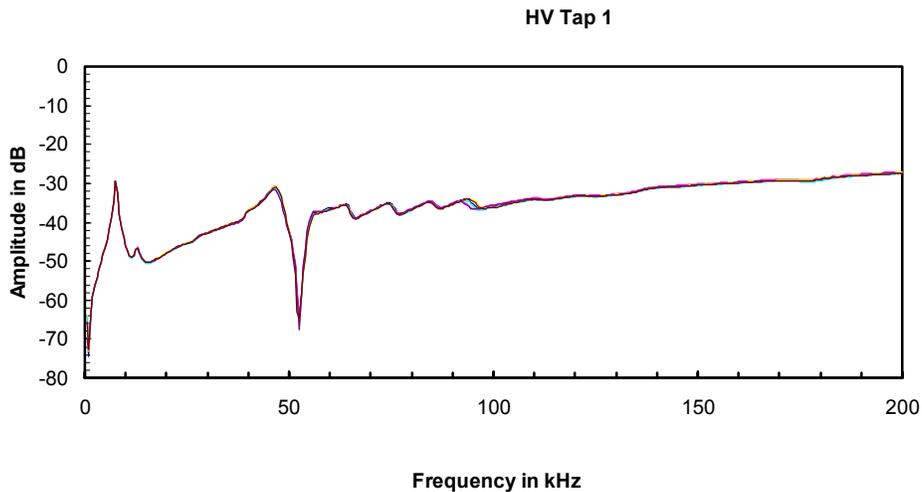
The transformer was relocated and SFRA tests again performed once the transformer had arrived on site.

Figure 13 shows all three phases before **and** after relocation. The chart contains six traces which are clearly very consistent.



**Figure 13 Before and After Plot in the 20 kHz Sub-band**

Figure 14 shows the 200 kHz region – again, all six traces are present: three phases before relocation and three phases after relocation. Clearly there is very good correspondence between the measurements. The variations between phases in the 100 kHz region are repeated after relocation, showing that no significant movement occurred during relocation.



**Figure 14 Before and After Plot in the 200 kHz Sub-band**

The results overall show very good consistency before and after relocation. There is no evidence from the SFRA, therefore, of any significant winding movement or distortion having taken place as a result of the relocation.

There was in fact an added value to the SFRA measurements made on this transformer in that during commissioning the transformer was overfluxed and there was a suspicion that there may have been some internal movement as a result of the excessive electrical stress.

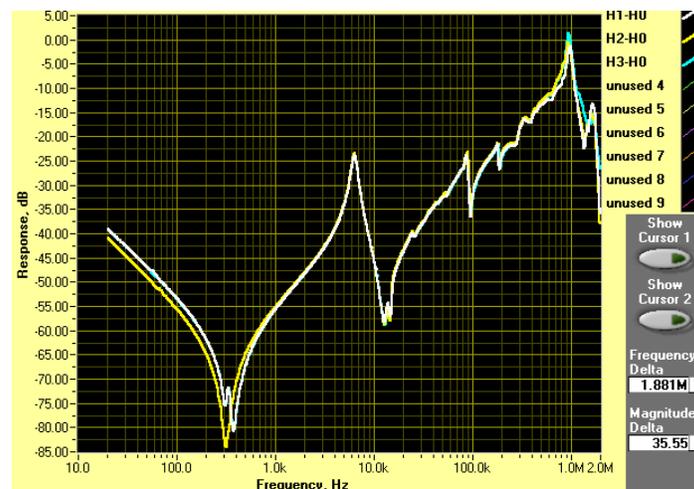
A further SFRA measurement was performed on this unit and showed no change in results from the previous versions. This gave confidence that the overstressing incident had not significantly affected the mechanical integrity of the windings.

### 6.3 Case Study 3: Transformer Assessment – use of Sister Transformer

A bushing failure on a GSU gave cause for concern about the mechanical integrity of the transformer windings. SFRA was used as part of a suite of electrical tests to assess the electrical insulation and mechanical integrity of the transformer.

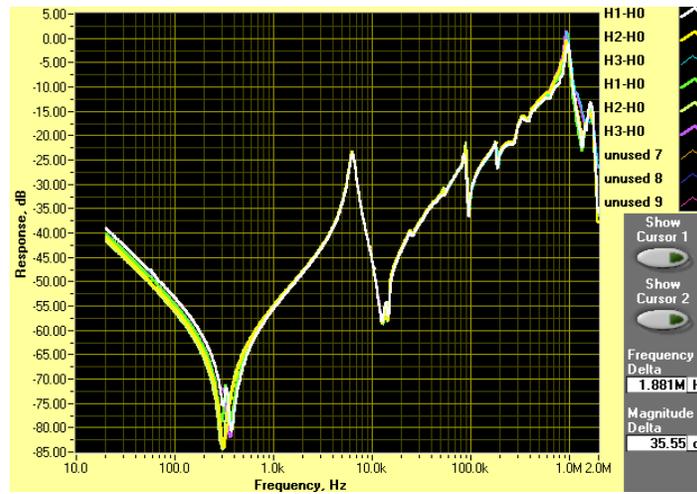
In this case, both the transformer under suspicion and a sister unit of the same design and vintage were available for testing. Extensive electrical tests took place, with SFRA used to confirm that no significant winding movement had occurred.

Figure 15, below, shows the overall results for the suspect transformer. There is good correspondence between the phases. The sub 1 kHz variations are typical of lower frequency responses where the center phase sees a single reluctance path in this inductive area, as shown in yellow with the single resonance, while the two outer phases show two resonances. See section “5.7 What causes variation in the 2 kHz range?”



**Figure 15 SFRA Results for HV Windings of Suspect Transformer**

Small variations are evident at higher frequencies, above 1 MHz, in the trace for the H3-H0 winding. These would normally be considered acceptable. To give support to the interpretation of the results, further SFRA measurements were made on the sister transformer. These results are given in Figure 16 which contains all 6 traces – 3 for the suspect transformer and 3 for the sister unit.



**Figure 16 SFRA Results – Comparison with Sister Unit**

Clearly there is very good correspondence between the two units. In fact, variation between phases in the suspect unit is mirrored in variation between phases in the known good transformer. The variation in the H3-H0 phase in the suspect transformer is seen again in the transformer known to be good. The six traces in Figure 16 are strong evidence that the suspect unit is mechanically sound. Additional results were gained through analysis of the LV windings. Overall, SFRA measurements have not revealed any significant winding movement or distortion. The suspect transformer was subsequently successfully returned to service.

## 7 Interpretation

There are general rules that can be applied to SFRA trace interpretation.

The first rule is “Don’t jump to conclusions”. SFRA is one tool in the toolbox and results should be used in conjunction with other test results – from exciting currents, power factors, turns ratio etc. Where there are differences between phases or between successive measurements on the same unit, the first question that must be asked is “What are the possible causes of the differences?” Tap positions may have changed; there may be design differences between ‘sister units’. Where baseline results are available, then any variation is clearly a cause for concern.

When interpreting a trace, it is important to make use of all the information present – to look at the whole picture. Small variations or displacements across a large frequency range may be much more important than a large variation in one part of the frequency range.

Resonances in an SFRA trace are related to the capacitances and inductances within the transformer. Variation in resonance peaks may be in terms of position or of amplitude – position variations are more of a concern as they imply a variation in the capacitance or inductance while amplitude variation is more likely to be related to good lead application.

Stray resistance when attaching the test leads may lead to variation in amplitude, but not normally resonant frequencies. Variation in cable shield grounds resistance may also introduce disparity in the results, particularly at higher frequencies. “Appendix 6: Test Issues and Precautions” looks at variations which may be due to test procedure.

In analyzing traces, lower frequencies tend to relate to larger objects; higher frequencies relate to smaller objects. In terms of size there is a general rule of thumb that, while reviewing a trace from left to right, from 20 Hz to 2 MHz, this corresponds to the core, clamping structure and yoke, main windings, tap leads and connecting leads. The actual position of resonances in the trace depends on the size of the transformer; lower MVA transformers tend to have their resonance shifted more to the higher frequencies. However, there are always exceptions to this ‘rule of thumb’ and individual traces should be inspected on their merits. More details are given in “Appendix 3: Measurements on Different Winding Types”.

## **8 What Doble offers**

Doble's M5100 Sweep Frequency Response Analyzer is the most reliable and robust SFRA system in the world. It offers state of the art hardware and software that produces repeatable results across the frequency range of interest, supported by world class engineers to assist with test procedures and result interpretation.

The most important aspect of frequency response analysis is to get valid results from a particular test for decision making purposes. This means that the results reflect the true response of the windings, and do not include associated test lead or equipment affects. After years of study and research, Doble has chosen the Sweep Frequency method for making the measurement, as other approaches have not yielded cost-effective systems or reliable results.

Doble offers the M5100 and the full support and service associated with Doble products. Results may be analyzed and interpreted using Doble's in-house experts who are able to reference an extensive library of SFRA results built up over years of testing a wide variety of transformers.

The Doble M5100 has a resolution that is logarithmic, remaining constant at 1.2% at every frequency. This means that resolution is maintained across the frequency range. The Doble M5100 software allows data to be displayed either in a log scale format or in a linear scale format.

The Doble M5100 gives consistent and reliable results from 10 Hz to the MHz range, allowing for interpretation in terms of key elements within the transformer: core, clamping structures, main and tap windings, internal support leads. Without this full range of frequency coverage, as provided by the Doble M5100, the test results are compromised.

The Doble M5100 software allows for display of the whole of the measurement made, or through an intuitive graphical interface allows particular sections to be viewed in detail. In addition the software displays sub-bands for those who are more comfortable viewing data in that way.

## **9 Conclusions**

Sweep Frequency Response Analysis is a powerful tool for use in analyzing transformer health and mechanical integrity. It has proven value in the field and factory, as indicated in the case studies given here.

The Doble M5100 test instrument produces reliable, robust and repeatable results. These cover the full range necessary to make transformer health diagnoses relating to the core, the windings and the tap changer.

Doble's in-house knowledge is extensive, and with a large reference library of results available for use, solid support is available for decisions made in the factory and in the field.

The Doble M5100 SFRA test set is a vital tool for today's engineer.

## 10 References

References from Doble Clients as to how they have benefited from SFRA in practice are available. Please contact the authors.

“Experience with Failure Prevention in Power Transformers using Frequency Response Analysis Technique”

Ernesto Perez, NorControl, S.A., Spain, Doble Client Conference 1998

“Transformer Winding Movement Detection by Frequency Response Analysis”

John Lapworth & Tony McGrail, National Grid Company, U.K., Doble Client Conference, 1999

“Case Study of Frequency Response Analysis Method”

Alain Moissonnier, EdF, France, Doble Client Conference, 1999

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Sokom An, Bonneville Power Administration, USA, Doble Client Conference, 1999

"Transformer Diagnostic Testing by Frequency Response Analysis"

Dick, E. P. and Erven, C. C, IEEE Trans PAS-97, No. 6, pp 2144-2153, 1978.

"Mechanical Condition Assessment of Power Transformers Using Frequency Response Analysis"

Lapworth, J. A. and Noonan, T. J., Doble Client Conference, 1995,

"Frequency Domain Analysis of Responses from LVI Testing of Power Transformers"

Richenbacher, A. G, Doble Client Conference, 1976,

## 11 Appendix 1: Theory & SFRA Fundamentals

The primary objective of SFRA is to determine how the impedance of a test specimen behaves over a specified range of applied frequencies. The impedance is a distributed network of active and reactive electrical components. The components are passive in nature, and can be modeled as resistors, inductors, and capacitors. The reactive properties of a given test specimen are dependent upon and sensitive to changes in frequency. The change in impedance versus frequency can be dramatic in many cases. This behavior becomes apparent when we model the impedance as a function of frequency. The result is a transfer function representation of the RLC network in the frequency domain.

### 11.1 RLC Networks

Frequency response analysis is generally applied to a complex network of passive elements. For practical purposes, we will only consider resistors, inductors, and capacitors as passive circuit elements, and they should be assumed ideal. These three fundamental elements are the building blocks for various physical devices, such as transformers, motors, generators, and other electrical apparatus.

It is important to understand the difference between the physical device and the mathematical model we intend to use. When large and complex systems are electrically analyzed, we are often faced with a poorly defined distributed network. A distributed network contains an infinite amount of infinitely small RLC elements. For example, transmission lines are generally distributed in nature. It is practical to model such distributed systems by lumping the basic RLC components together, resulting in a lumped network. Lumping elements together for a single frequency is a trivial task. However, when system modeling requires spanning over a significant frequency interval, then producing a suitable lumped model becomes difficult.

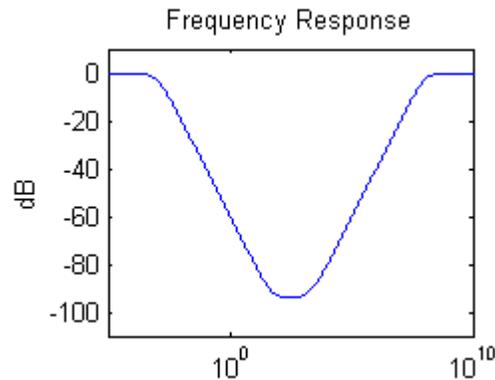
There are eleven forms of the basic lumped network. These eleven forms are represented in Table 1.

Single Element	Series Combination	Parallel Combination
R	RL	RL
L	RC	RC
C	LC	LC
	RLC	RLC

**Table 1 Basic forms of lumped networks**

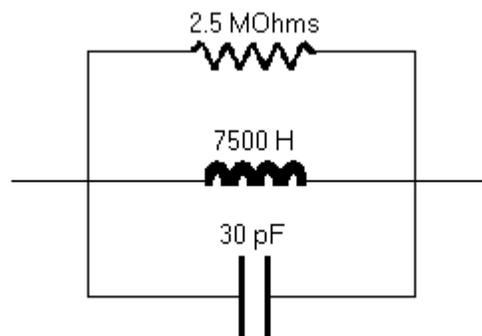
As the model increases in complexity, these forms can be combined. They can be connected in series, parallel, or series/parallel to produce the desired model. RLC modeling as it relates to FRA testing is most easily seen in the low frequency range, while testing a high voltage winding on a typical transformer. Most transformers produce a very distinct resonance in this frequency range.

Figure 17 is plotted logarithmically and illustrates a second order resonance.



**Figure 17 Frequency Response with Second Order Resonance**

Figure 18 gives the equivalent parallel RLC circuit which best represents such a resonance.



**Figure 18 Equivalent RLC Circuit for Second Order Resonance**

Consequently we can see that the frequency response may be modeled using discrete components.

## 11.2 Time and Frequency Domains

System responses can be represented either in the time domain or in the frequency domain. Voltage and current signals can be observed over time, thus resulting in a signal versus time or time domain response. Any signal can be represented by a sum of harmonically related sinusoids, at varying magnitudes and phases. When a signal is represented by a sum of sinusoids, the result is displayed and represented in the frequency domain. Various tools and techniques can be applied in either case for analyzing the responses. Differential equations and convolutions are applied to  $n^{\text{th}}$  order linear systems in the time domain, while Fourier and Laplace methods are used extensively for linear systems in the frequency domain.

The time domain and frequency domain are related collectively by the transform-pair relationship. Using the Fourier relationship as an example, the function  $F(j\omega)$  is the Fourier transform of  $f(t)$ , and  $f(t)$  is the inverse Fourier transform of  $F(j\omega)$ . The transform pair is defined by Equation 1 listed below.

$$F(j\omega) = \int_{-\infty}^{\infty} e^{-j\omega t} f(t) dt \Leftrightarrow f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{j\omega t} F(j\omega) d\omega \quad \text{Equation (1)}$$

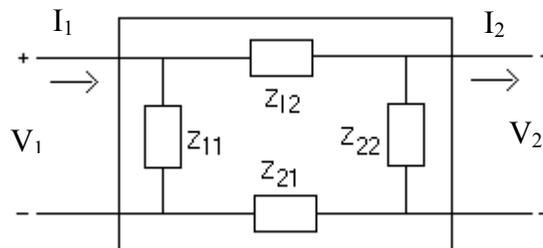
The energy associated with  $f(t)$  is proportional to the energy associated with  $F(j\omega)$ . To better understand the relationship between the domains, the energy correlation should be examined closely. The energy of a signal can be represented by the sum of its individual orthogonal components, where inversely, the sum of such components, creates an equivalent time domain representation. The energy of a signal or system can be obtained by either  $f^2(t)$  over time or by integrating  $F^2(j\omega)$  multiplied by  $1/(2\pi)$  over all frequencies. This relationship is known as Parseval's theorem, which compares the total energy of a time domain system to a frequency domain system. Parseval's theorem is represented by Equation 2, shown below.

$$\int_{-\infty}^{\infty} f^2(t) dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} |F(j\omega)|^2 d\omega \quad \text{Equation (2)}$$

Often, it is difficult to analyze system responses displayed in the time domain, while the frequency domain equivalent may prove to be much easier. Identifying predominant system features, such as resonance, by time domain methods is not easily accomplished. When the same resonance is displayed using frequency domain techniques, the resonance characteristics are identified with clarity and confidence. Noise and harmonic content are other examples of where the frequency domain analysis is beneficial.

### 11.3 Two Port Networks

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, 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 19 illustrates a two-port network.



**Figure 19 Two-Port Network**

$z_{11}$  ,  $z_{22}$  ,  $z_{12}$  , and  $z_{21}$  are the open-circuit impedance parameters, and can be determined by setting each current to zero and solving Equation 3.

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}, \text{ where} \quad \text{Equation (3)}$$

$$z_{11} = \left. \frac{V_1}{I_1} \right|_{I_2=0} \Rightarrow z_{12} = \left. \frac{V_1}{I_2} \right|_{I_1=0} \Rightarrow z_{21} = \left. \frac{V_2}{I_1} \right|_{I_2=0} \Rightarrow z_{22} = \left. \frac{V_2}{I_2} \right|_{I_1=0}$$

These impedances are formed by the complex RLC network of the specimen. It should be noted that the negative terminals in the above diagram are short-circuited when transformers are tested – through the transformer tank. The transformer tank is common for both negative or lower terminals in Figure 19. The transformer tank and lead ground shields must be connected together to achieve a common-mode measurement. This assures that no external impedance is measured. Applying the connection in this manner helps reduce the effects of noise. It is very important to obtain a zero impedance between the lower or negative terminals to assure a repeatable measurement. Applying grounds during testing will be discussed further in “Appendix 6: Test Issues and Precautions”.

#### 11.4 Transfer Function

The transfer function of a RLC network is the ratio of the output and input frequency responses when the initial conditions of the network are zero. Both magnitude and the phase relationships can be extracted from the transfer function. The transfer function helps us better understand the input/output relationship of a linear network. The transfer function also represents the fundamental characteristics of a network, and is a useful tool in modeling such a system. The transfer function 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 4.

$$H(j\omega) = \frac{V_{output}(j\omega)}{V_{input}(j\omega)} \quad \text{Equation (4)}$$

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 occurs at the roots of the polynomials. The roots of the numerator are referred to as “zeros” and the roots of the denominator are “poles”. 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 we measure the transfer function  $H(j\omega)$ , 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. It must be noted that when using the voltage relationship,  $H(j\omega)$  is not always directly related to  $Z(j\omega)$ . For  $Z(j\omega)$  to be directly related to  $H(j\omega)$ , a current must be substituted for the output voltage and then Ohms Law can be realized. However, FRA uses the voltage ratio relationship for determining  $H(j\omega)$ . Since the FRA test method uses a  $50\ \Omega$  impedance match measuring system, the  $50\ \Omega$  impedance must be incorporated into  $H(j\omega)$ . Equation 5 shows the relationship of  $Z(j\omega)$  to  $H(j\omega)$ .

$$H(j\omega) = \frac{V_{output}}{V_{input}} = \frac{50}{Z(j\omega) + 50} \quad \text{Equation (5)}$$

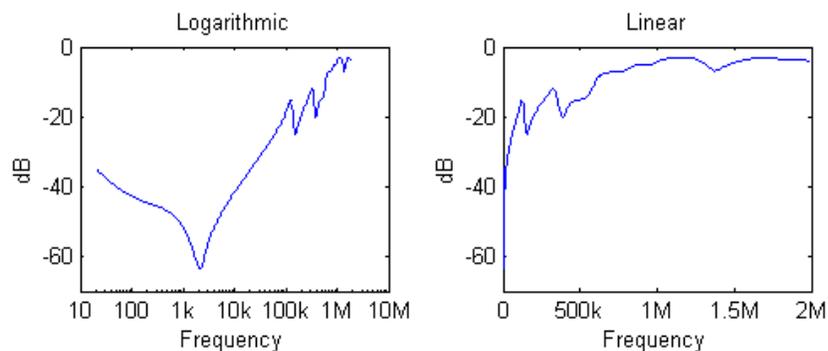
The preferred method of engineers is to use the Bode Diagram. The Bode Diagram plots the magnitude and phase as follows:

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

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

The Bode Diagram takes advantage of the asymptotic symmetry by using a logarithmic scale for frequency. Before the day of computers and data processing, the Bode method was the only effective way to estimate a transfer function. The frequency scale is plotted by decades, such as 1, 10, 100, 1k, 10k, etc. The effect of poles and zeros are very unique to the Bode Diagram. Poles and zeros create a 20 dB per decade change for a single root. Poles cause  $-20$  dB per decade deficit, while zeros produce a gain of 20 dB per decade. Plotting the phase relationship with the magnitude data will help determine whether the system is resistive, inductive, or capacitive. It is often useful to compare resonance in the magnitude plots with the zero crossings in the phase relationship.

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. However, when zooming in closely, a linear plot may help to simplify the plot interruption by having evenly spaced frequency ticks. Figure 20, shown below, compares a logarithmic plot to a linear plot over a substantial frequency range.



**Figure 20 Logarithmic vs. Linear Plotting**

## **12 Appendix 2: Frequency Response Analysis: Sweep v. Impulse**

There are two basic methods for measuring frequency domain characteristics. One method sweeps the frequency spectrum, while the other uses the Fast Fourier Transform (FFT) technique.

The utility industry refers to the sweep-sine method as Sweep Frequency Response Analysis (SFRA) and the FFT method as Impulse method. These names have been adopted by the transformer diagnostic community, and best describe the applied techniques.

### **12.1 Sweep Frequency**

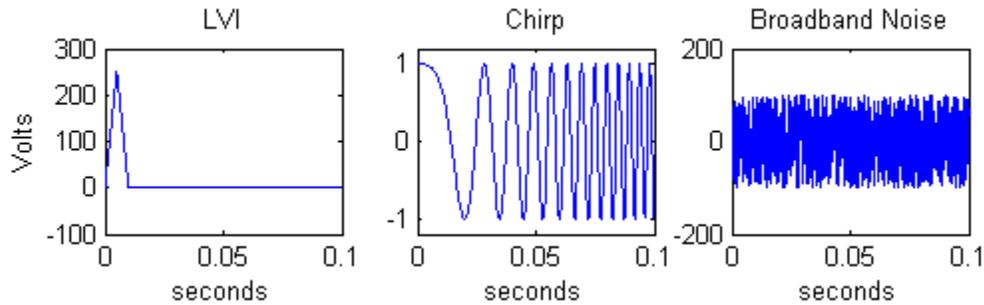
The Sweep Frequency or Sweep Frequency Response Analysis (SFRA) method performs measurement at each frequency point of interest. The excitation source generates a sinusoidal waveform at a constant magnitude. Since the source is constant and can be maintained for a specified amount of time, the digitizers have ample time to adjust their gain settings, resulting in higher dynamic range performance.

A feature of this precise measurement technique is that it takes a little longer to produce a measurement. An SFRA scan could take a few minutes depending on the settings used, such as bandwidth and the number of points collected. The test will run slower at low frequencies and will obtain data more rapidly as frequency increases.

The bandwidth is defined as the range of frequencies that are permitted to enter the measurement receiver. The bandwidth setting acts like a band-pass filter, which prevents any unwanted noise from entering the receiver. Ideally, the measurement receiver would like to pass only the frequency of interest. Reducing or tightening the bandwidth requirement exponentially increases test time. We must compromise between test time and resolving small signals. SFRA is optimized by letting the bandwidth be a function of frequency, which takes place automatically within the Doble M5100 test set.

### **12.2 Impulse**

The term Impulse is derived from a subset associated with the FFT method for determining transfer functions. When considering the entire FFT family, the impulse subset is one method for testing transformers. The subset name refers to the signal type used for excitation. Other FFT subsets include chirping and broadband noise. Fast Fourier Transforms are applied to the input and output responses which are generated by one of the above mentioned excitation signals. The bins of each FFT will be compared against the other resulting in a transfer function. Figure 21 illustrates the impulse, chirp, and broadband noise signals, which are used for FFT excitation.



**Figure 21 Excitation Signals for the FFT Testing Method**

Impulse testing is conducted by generating an impulse with a predetermined rise time and duration. A typical impulse can have a peak amplitude of 200 - 300 V pk with a rise time less than 200 ns and a duration less than 20  $\mu$ s. This impulse will be applied to an RLC network, and both the input and output responses will be recorded. An FFT will be applied to both responses and the discrete frequency components will be extracted. The components of each response will be matched by bin and compared. The magnitude and phase relationship will be determined for each match. With this information, a transfer function can be plotted.

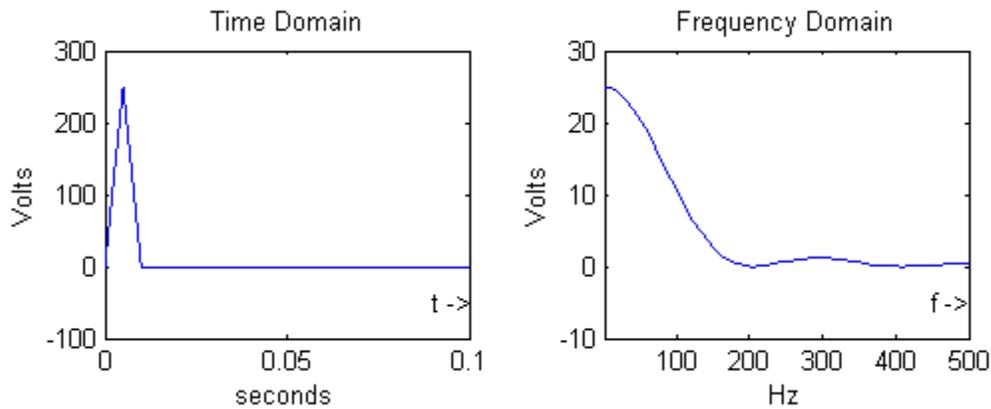
The primary advantage of the Impulse method can be the speed at which data is collected and processed. Unfortunately, the data collected is of limited value due to imperfections and inadequacies in the pulse generation and measurement systems. Once the input and output responses are collected, the remaining time is spent on the FFT calculation. The data collection process can take as little as 100 ms. Depending on the processor speed, the FFT calculations can be completed in several seconds, while slower processors may take a few minutes. For the Impulse to be effective the processor and the analog to digital converter (A/D or digitizer) must both possess speed.

If the application requires a large variation in magnitude, such as 70 dB or more, then the Impulse method is less accurate. The impulse method compromises dynamic range. The resolution of the digitizer must remain constant and cannot increase as the signal energy decreases. Increasing the bit count will help to improve resolution. The bit count required is a function of the expected peak amplitude and the desired attenuation level. To obtain reasonable results across the frequency range from 10 Hz to several MHz would require *very expensive* hardware and would still provide poor data relative to sweep methods.

*Another* limitation of the impulse method comes from the excitation source. The source must contain all of the frequencies of interest, and at the same time all of the frequency components must add up to the source; this statement relates to Parseval's theorem – see Section 11.2. The energy in the impulse source diminishes quickly as the frequencies of interest increase. Noise and environmental effects can easily influence the transfer function at the frequencies of low energy. The impulse techniques will be most accurate at low frequencies and magnitudes that best fit the digitizer's specified gain. However, the accuracy comes at another cost – a *further limitation* is that as the bins which are used

in the Fourier Transform process are uniformly spread across the frequency range, there is relatively a large ‘gap’ between bins at lower frequencies. This results in very poor resolution at those low frequencies, making analysis unreliable at best and almost impossible in areas related to the core.

The frequency components of an impulse can be best estimated by combining the leading edge of a step function and the trailing edge of a triangular waveform. The frequency domain result is a hybrid combination of the “ $\text{sinc}(f)$ ” and “ $\text{sinc}(f)^2$ ” functions. Figure 22 graphically shows the relationship between the time and frequency domain for a typical impulse.



**Figure 22 Impulse Time and Frequency Domain**

The frequency domain plot in Figure 22 shows that all significant energy is contained within the first few hundred bins. It should be observed that the exciting energy of an impulse decays quickly. The decreasing energy components are easily seen when they are displayed in the frequency domain. The input signal is already attenuated by the harmonic characteristics of the impulse at higher frequencies. The transformer’s transfer function will attenuate the output response even further. This important energy will be driven into the noise floor *compromising the impulse measurement further*.

## 13 Appendix 3: Measurements on Different Winding Types

Most people immediately think of winding measurements as being only associated with the high-voltage and the low-voltage windings. When considering SFRA measurements, winding measurements realistically consist of five categories and not just two. The winding categories are high-voltage, low-voltage, inter, series, and common.

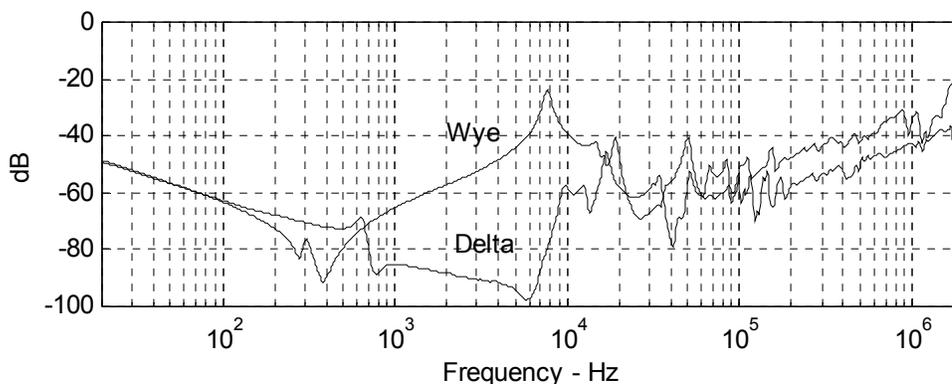
Short circuit measurements made on one winding while short circuiting another winding are a variation on interwinding measurements.

It should be noted that inter-winding measurement is not a true winding measurement, but rather the transfer impedance between two windings. The series and common winding measurements describe the SFRA application as it is applied to auto transformers. Regardless, certain expectations can be made for each.

These measurement types produce some predictable characteristics and properties. Understanding these properties will minimize testing error and may help identify problems. The following expectations exist for each of the following categories.

### 13.1 High-Voltage Winding

High-voltage winding measurements have greatest attenuation as compared to low voltage and tertiary windings. Most traces start between  $-30$  dB and  $-50$  dB and are initially inductive. High-voltage windings are much larger in overall size, which contributes to greater complexity in its distributive network. High-voltage winding measurements generally produce steeper resonances and more of them as compared to its low-voltage counterpart. Figure 23 illustrates these features.

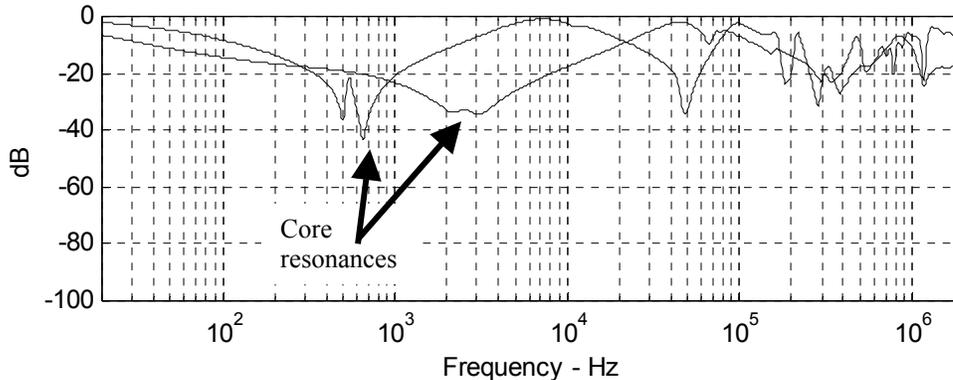


**Figure 23 High-Voltage Winding**

The traces shown in Figure 23 are from different test specimens. Both traces are from 230 kV core-form transformers, however one trace is from a delta connected configuration and the other is from a wye connected configuration.

### 13.2 Low-Voltage Winding

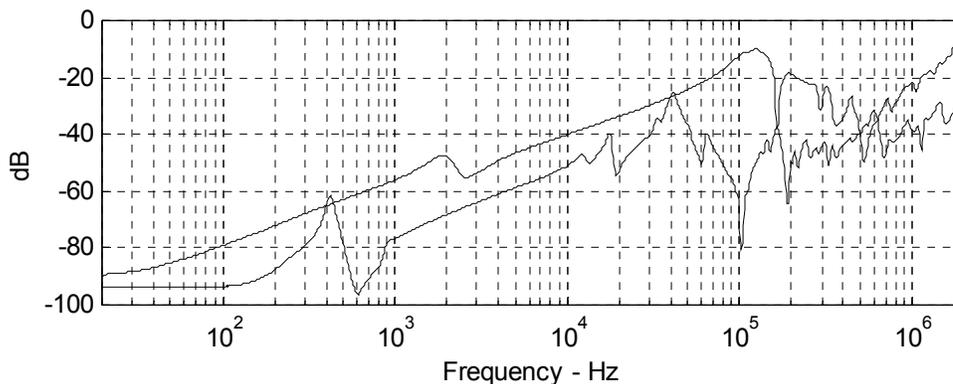
Low-voltage winding measurements have least attenuation as compared to the other categories. Most traces start between  $-5$  dB and  $-15$  dB and are also initially inductive. This characteristic is due to the low impedance property of the high current side of the transformer. The first peak after the core resonance generally approaches  $-5$  dB to  $0$  dB and is concave and smooth. As compared to the high-voltage winding response, the low-voltage winding fewer fluctuations and is slight smoother. Figure 24 illustrates these features. Again, both traces in this figure are from different transformers.



**Figure 24 Low-Voltage Winding**

### 13.3 Inter-Winding

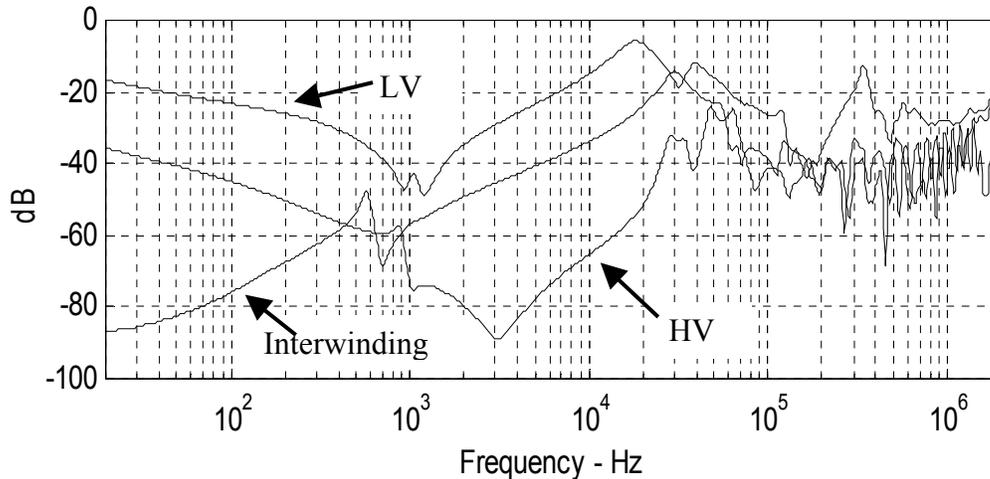
Inter-winding measurements always start with high attenuation, between  $-60$  dB and  $-90$  dB, and are capacitive. If electrostatic interference is present, it will show up at  $60$  Hz and at the associated harmonics of  $60$  Hz during this measurement. Figure 25 illustrates these features. These traces are very common; most inter-winding traces adhere to one of the basic shapes shown below.



**Figure 25 Inter-Winding**

Figure 26 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

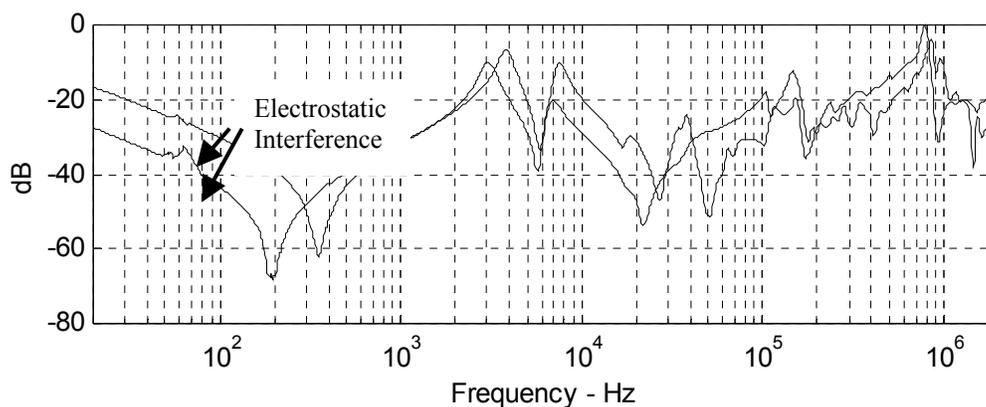
relationship. It can be seen that the low-voltage winding has consistently lower attenuation than the high-voltage winding. Also, low-voltage winding is much smoother at higher frequencies. This example was taken from a 10 MVA auxiliary transformer.



**Figure 26 Trace Relationship**

### 13.4 Series and Common Winding

The series and common winding measurements are grouped together because of their similarities. These measurements are associated with auto transformer. The naturally low turns ratio of an auto transformer cause the series and common measurements to be similar. However, if an LTC is present on either winding, the similarities will be somewhat affected by the tap windings. Figure 27 illustrates these features, and were obtained from a General Electric 440MVA 345 kV auto-transformer. Electrostatic interference was present during testing and is seen at 60 Hz.



**Figure 27 Series and Common Winding**

## 14 Appendix 4: Data Collection and Display

The goal is to select the test parameters that will produce the most accurate transfer function within a reasonable time frame. Data must also be collected with reasonable resolution. Depending on the test parameters, such as the number of points collected and the IF bandwidth (BW), the SFRA test instrument makes the best transfer function approximation with the available data. For example, collecting more frequency points for a given frequency band produces a smoother trace; it might be possible to miss the true resonance if fewer data points are collected due to the discrete nature of the frequency points. This is a particular failing of the impulse method, losing resolution at lower frequencies.

Selecting the correct BW is very important, because it helps lower the noise floor by filtering the test instrument inputs. The BW setting also removes unwanted spikes, harmonics, and spectral noise. The BW has to be selected carefully and should be a function of the measurement frequency. It is recommended that the BW is set equal to or less than 1/5 of the measurement frequency. If the measurement frequency is 500 Hz, then the bandwidth should be 100 Hz or less. It should be noted that decreasing the BW would result in a slower test. To maximize the effectiveness and efficiency of an SFRA test, the BW should be dynamic with the change in frequency. The data can be collected and displayed either logarithmic or linear. Each data format has specific features such as:

### 14.1 Logarithmic

- Allows large frequency bands to be collected and displayed.
- Produces symmetric and asymptotic plots (Bode Diagram).
- Collects more points at lower frequencies and fewer at high frequencies.

### 14.2 Linear

- Data contains great detail.
- Poor resolution at low frequencies.
- Great resolution at higher frequencies.
- Multiple bands must be collected.

Past experience of Doble clients has favored the linear format. Data has been collected and displayed in 5 separate frequency bands. The frequency bands overlap which compensates for poor resolution at the lower frequencies in each band. This is a constraint of the measuring equipment that was traditionally a HP Network Analyzer.

The recommendation of the EuroDoble subcommittee which looked at data collection is to follow the test parameters listed in Table 2; however, the IF bandwidth column is not published in the test guide.

Measurement Bands	# Points	Frequency Range	IF Bandwidth/ Hz
1	400	10 Hz – 2 kHz	2
2	400	50 Hz – 20 kHz	10
3	400	500 Hz – 200 kHz	100
4	400	5 kHz – 2 MHz	1000
5	400	25 Hz – 10 MHz	3000

**Table 2 Test Parameters for Linear Data Collection**

The same data collected with the linear data format parameters may be displayed logarithmically. The data is collected in one band. The logarithmic test parameters are listed in Table 3.

Measurement Bands	# Points	Frequency Range	IF Bandwidth
1	800 – 2000	10 Hz – 10 MHz	Freq/(>5)

**Table 3 Test Parameters for Logarithmic Data Collection**

It should be noted that the data display, whether it be logarithmic or linear, is a function of user preference. As long as an effective bandwidth is selected and enough points are collected, either format is valid.

The Doble M5100 test instrument can be configured to display data in either logarithmic or linear format; it also displays data both as overall traces or as sub-bands and allows for zooming in on particular areas of interest.

## **15 Appendix 5: SFRA History**

Frequency Response measurements were first investigated in depth by Dick and Erven at Ontario Hydro in Canada in the 1970's. For some reason, their work was never taken up widely.

In the 1980's the Central Electricity Generating Board (CEGB) in the UK took up the measurement technique and applied it to transmission transformers. The French also began to pursue measurements at the same time. On the break up of the CEGB in the early 1990's work in FRA was taken up by National Grid in the UK and resulted in several papers at Doble Client Conferences. The technique has been spread further through EuroDoble conferences and client meetings and several utilities took up the technique.

Many early practitioners tried impulse systems, and have continued to try them up to the present. Though appealing in terms of speed, they have never been able to match the range, resolution or repeatability of sweep methods and continue to reject such methods.

As the basic technique developed by early users required laboratory based equipment such as HP network analyzers, which were robust, but not field hardened, and required specialist operators. Upon a successful program of product development and field trials, Doble stepped in to provide field engineers and staff with a reliable and robust tool for transformer analysis – the M5100. This outperforms the HP in terms of measurement characteristics and field usability.

## 16 Appendix 6: Test Issues and Precautions

As with any electrical test, issues, such as cables, grounding, noise, and interference must be given serious considerations. We are testing in harsh mechanical and electrical environments and the test instrument is designed to be extremely sensitive. Unlike power factor testing, SFRA test methods cannot cancel noise or interference from the measurement, as they are an inherent part of the measurement being made. Being able to coexist with such issues will help increase the quality and interpretation of the measured results. The Doble M5100 is designed to do just that.

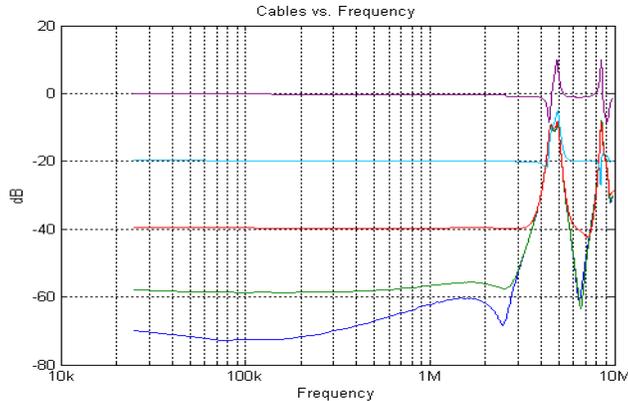
### 16.1 Test Lead Effects

50 Ohm impedance matched test leads are used. Either a RG58 or RG238/U RF coaxial cable with the shields grounded to the instrument chassis can be used. The RG58 is a much smaller cable; it is less durable, but easier to handle. The RG238/U is much harder to handle, especially in cold weather. It should be appreciated that the SFRA measurement requires a matched impedance signal cable, and performs a single-ended measurement, i.e., the signal with respect to the instrument ground. Thus, the shield of the signal cable must be connected to the chassis via RF BCN connectors.

Practical field experience indicates the leads may be 60 ft. in length, with shield grounds being at least 8 ft. long. This length has been selected as being the shortest to test the largest transformers from a location on the ground adjacent to the unit. Nevertheless, it is the lead length that determines the maximum effective frequency. At lengths of 60 ft., the cable approximates the wavelengths of the higher measurement frequencies, and there is probably little to be gained from the 2-10 MHz scan. As long as the cable is less than  $\frac{1}{4}$  of a wavelength in length, then the short cable approximation can be used. At lengths greater than  $\frac{1}{4}$  of a wavelength, phasing effects start to occur. It turns out that at 60 ft., the frequency cutoff with respect to wavelength is approximately 2 MHz. Previous work which attempted to produce repeatable results up to 10 MHz showed variable results.

Figure 28 illustrates the effects of the cables at higher frequencies; different attenuation levels are plotted to compare what influence the cables have on the noise to signal ratio. The attenuation was accomplished by a 50  $\Omega$  impedance matching resistor divider network. As can be seen, poor cables will influence results; good cables will have almost zero effect on results into the MHz range.

The Doble M5100 test set comes complete with cables that have almost zero effect on results into the MHz range.



**Figure 28** High Frequency Effects on Cables

## 16.2 Grounding

Proper grounding of the test instrument is essential. As discussed in the introduction of two-port networks, we desire zero impedance across the negative or lower terminals. This can be achieved in many different ways.

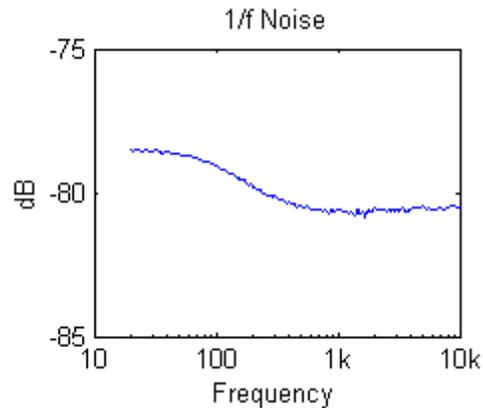
Earlier experience has shown that grounding the lead ends to the bushings is not always effective. If this technique is used, it is required that the bushing flange be solidly grounded to the transformer tank. Often, a small impedance is present. Also, the ground clamp must solidly bite into the bushing flange. Any paint or contamination on this surface can affect the measurement. Good test procedures offset this possible problem.

## 16.3 Noise and Interference

Noise and Interference can be introduced into a measurement by various means. Noise and interference influences a measurement by one of the following vehicles:

- Generated by the measurement instrument and coupled directly.
- Stray electrostatic and electromagnetic fields.
- Connection characteristics of the leads.

For simplification purposes, noise and interference should be considered separately. Noise has two categories white (or broadband) noise and  $1/f$  or low frequency noise. Because SFRA testing takes place in harsh electrical and mechanical environments, on average, the white noise floor appears at  $-80$  dB. Measurements below  $-80$  dB are often contaminated with a “hash” like appearance. However, averaging techniques have been proven useful in reducing the effects of white noise below  $-80$  dB.  $1/f$  noise is a phenomenon that has a linear effect on lower frequencies.  $1/f$  noise appears as a pole, in control theory terms, affecting frequencies below 300 Hz, which are heavily attenuated. Figure 29 below illustrates the effect of  $1/f$  noise. The test specimen is a 400 k $\Omega$  load.



**Figure 29 1/f Noise**

Due to the sensitive nature of a SFRA instrument, interference cannot be avoided. The test set is immune to interference, but the test object – a transformer winding, will pick up any interference present with a broadband less than 10 MHz. Interference, such as mechanical vibration, power line pick-up (50 Hz and 60 Hz), and RF (AM/FM broadcasts), are usually present during testing. They are most noticeable when the measured output signal is attenuated. Power line pick-up will often have several harmonics included.

Consequently noise cannot be eliminated – its affects may only be reduced. By using a sweep approach, noise contamination is limited to just those frequencies where it is present. An impulse approach allows the noise to contaminate the whole frequency range, compromising the measurement.

## 17 Appendix 7: Trace Comparisons

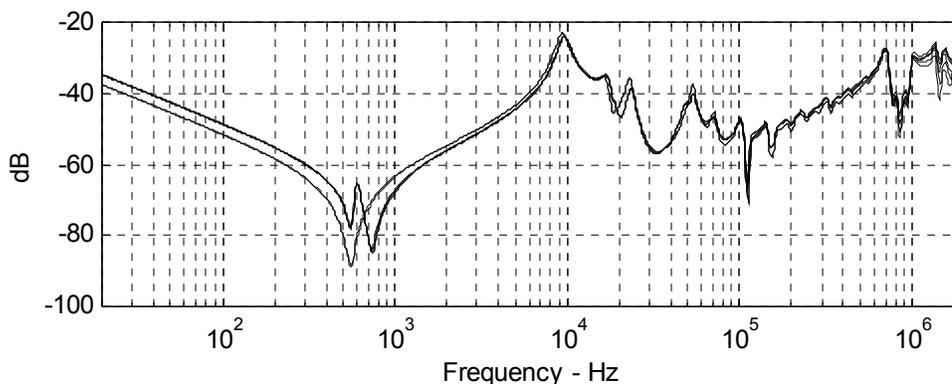
Trace comparison is the primary method for the analysis of SFRA results. Comparisons can be made against the baselines and previous data, sister unit results, and phases. Assuming the test equipment provides repeatable results, the initial expectation is that any data comparison should result in near perfect overlays.

Our database indicates that various levels of expected comparison exist. The level of expected comparison may be categorized by the following:

### 17.1 Baseline Data

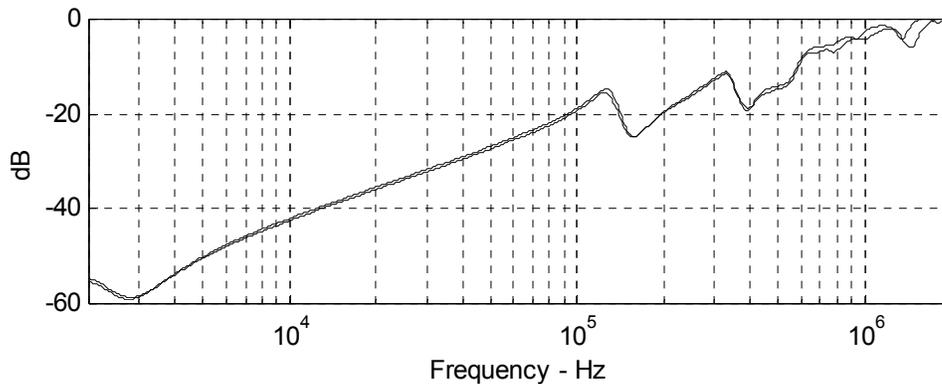
Baseline or previous data should be repeatable. If internal movement or change does not occur within test specimen, the matched traces should overlay well. Match traces are defined as SFRA results obtained from the same point of contact. An example would be two scans collected from the same winding, such as H1-H3, on different test dates.

Data is collected before and after transformer relocation is expected to overlay well. Any variance in such comparisons indicate a problem. One exception is caused by the magnetic circuit and the state of the remnant magnetism occurs at low frequencies and should be overlooked – see section 5.7 “What causes variation in the 2 kHz range?” Magnetization and temperature change can cause the beginning of the trace to be slightly offset in certain cases. Figure 30 illustrates a before and after relocation response of a set of high-voltage windings. The results were not only obtained on different test dates, but also were obtained with different test sets. Phase to phase variations exist, but there are no differences before and after relocation. See also section 6.2 “Case Study 2: Assessment and Relocation of a GSU”.



**Figure 30 Comparison to Baseline**

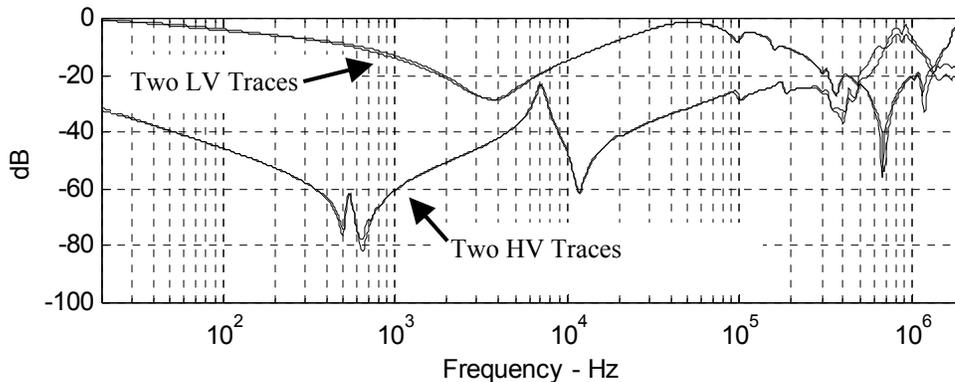
It should be noted that the LTC and DETC position influences the results. If the test results are obtained in different tap positions, expect variation. Figure 31 shows two traces collected in different tap positions; the difference is small, but noticeable at frequencies greater than 500 kHz. The DETC was moved from position 3 to 5.



**Figure 31 Different DETC Positions (3 & 5)**

### 17.2 Sister Units

Sister unit results are also expected to compare well. Our database of sister units shows very little difference between matched scans. All tests on sister units were conducted with the **LTC and DETC in the same position**. If the results are magnified small offsets can be noticed, but for the most part they are similar. Figure 32 demonstrates the similarities of sister units. Each plot consists of two high-voltage winding traces and two low-voltage winding traces. See also section 6.3 “Case Study 3: Transformer Assessment – use of Sister Transformer”.



**Figure 32 Comparison of Sister Units**

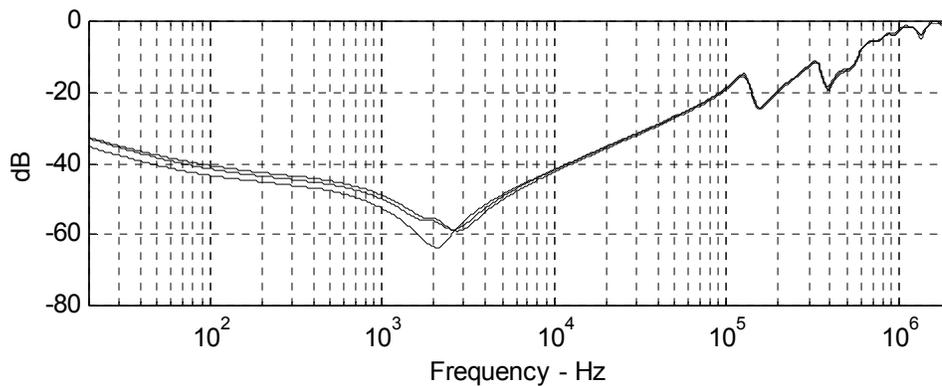
### 17.3 Phase

Phase comparisons are the most difficult and are open to subjective analysis. Phase results overlay reasonable correspondence, but often deviate.

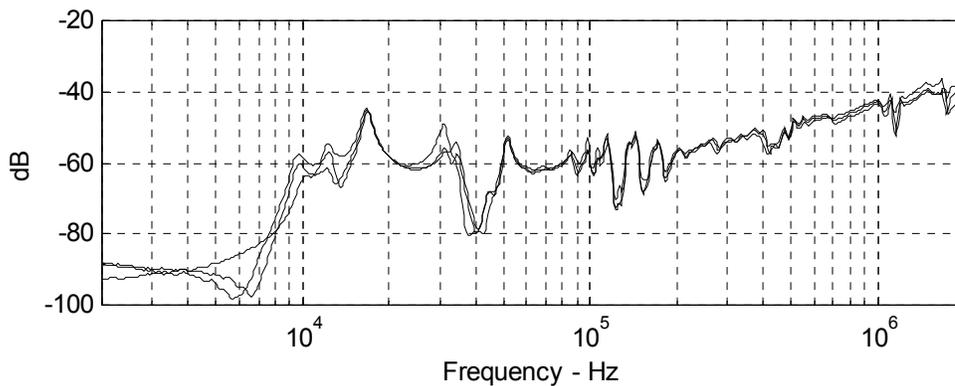
The center phase, especially in core type transformers, exhibits the most deviation when comparing all three phases. Often, the two outer phases compare. Different flux paths seen by each phase contribute to the observed differences. The affects of the core are

expected at the lower frequencies, however the core influence may reach into the mid-range up to 100 kHz in some cases.

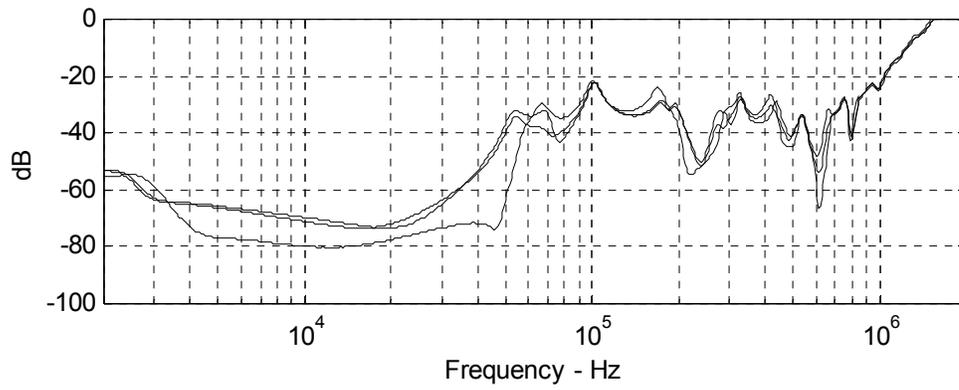
The actual windings of a three phase transformer are almost identical, but the connection scheme between phases are very different. As an example, the phases of a wye winding are all at different distances from the neutral; LTC connections fall into the same category. Thus, since the winding are not equilaterally spaced, the varying lead length entering and leaving the windings influence the individual transfer function of each winding. Figure 33, Figure 34 and Figure 35, below, illustrate varying levels of phase comparison. They are ordered from best to worst, respectively. Experience has shown that phase comparison appears to be a function of the overall physical size and complexity of the transformer.



**Figure 33 Good Phase to Phase Comparison**



**Figure 34 Fair Phase to Phase Comparison**



**Figure 35 Poor Phase to Phase Comparison**