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On-line Frequency Response Analysis (OLFRA)
with
Application to Transformer End-of-life Predictive Maintenance (PdM)

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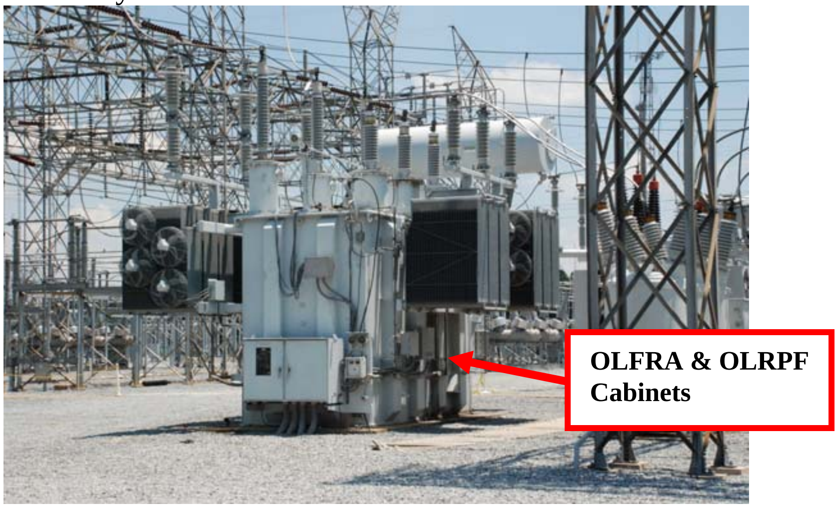
Abstract
Frequency Response Analysis (FRA) has traditionally been an off-line (transformer de-energized) test technique to determine winding deformation due to transformer transportation or permanent winding changes due to transformer through-fault conditions.

The new NEETRAC/JMX FRA method is an on-line (transformer energized) technique designed to perform winding movement diagnostics while the transformer remains in service. The technique can provide a yearly condition assessment of transformer winding deformation and therefore provide a new input for on-line end-of-life assessment.

The unique method uses induced lightning and routine substation maintenance switching as the test source for winding FRA determination. Winding test results are usually obtained in a time period of three months to a maximum of one year. Off-line baseline tests with the on-line equipment can also be performed when the equipment is installed and again during any planned or unplanned outages for baseline comparisons.

The OLFRA equipment remains on the transformer to indicate for significant winding deformation after damaging through-faults and for significant winding aging changes as a precursor to a transformer fault or as an indicator for end-of-life. In addition, the OLFRA equipment has an option as a high voltage wide band bus transient recorder. An example of a 230 kV capacitor breaker pre-strike is given.

The NEETRAC/JMX OLFRA Equipment
A typical installation on a 230/115 kV, 300MVA, auto-transformer is shown in **Figures 1-3.** OLFRA and transformer bushing on-line relative power factor (OLRPF) are connected simultaneously in this installation.



230/115 kV, 300MVA Auto
Figure 1

OLFRA & OLRPF Cabinet Locations
Figure 2

OLFRA Cabinet Equipment
Figure 3

The industrial rated computer, digitizers, and associated filters & attenuators are shown in **Figure 3**. The communication to the OLFRA and OLRPF equipment is by wireless 3G. A results summary is kept on a web site bulletin board that is password protected. The users can access the results in the form of winding frequency versus magnitude and phase curves on the web site. A green, yellow, red automatic alarm status for SCADA is under development.

The transformer bushing OLRPF is usually installed to work simultaneously with OLFRA since much transformer winding damage is caused by bushing failures and the failure mode of a bushing can affect certain frequency ranges of the winding OLFRA results before the bushing fails. It is expected for the future to add determination of bushing condition by its FRA contribution to the winding FRA result. The single bushing coupling interface has also been designed to add partial discharge (PD) to the mix. A technique to combine OLFRA, OLRPF, and PD has been developed and will be installed in the near future.

The problems with test repeatability with traditional off-line FRA is primarily due to test lead orientation and more importantly the test grounding techniques used [1]. These problems are not present with OLFRA since the leads remain the same with the same configuration for all test results.

Winding test results are usually obtained in a time period of three months to a maximum of one year after installation. Off-line or baseline tests with the on-line equipment can also be performed when the equipment is installed and again during any planned or unplanned outages for baseline comparisons. The on-line test results can be compared to the initial baseline test or to another on-line test result. So no outage is required to perform future winding FRA. If a transformer differentials out for unknown reasons, a fast winding FRA can be performed with the OLFRA equipment by using a transient generator for signal inputs to the transformer bushings. This particular off-line FRA can be performed with the bushing jumpers AND safety grounds attached. The only requirement is that a previous baseline FRA must be stored for bushing jumpers and grounds attached for comparison. This “grounded” baseline test can be easily performed along with the normal baseline test at the time of equipment installation.

The Unique NEETRAC/JMX OLFRA Method

The unique OLFRA method uses normal switching operations on the system, such as capacitor bank and reactor operations, along with induced lightning transients from local thunder storms for the FRA test signal source. The patented technology [2, 3] is unique in that it can perform FRA signatures on transformer windings using a variety of input waveforms with different time and amplitude characteristics.

The software uses Spectral Density Estimates (SDE’s) using the optimum transfer function / least-squares models. These are transfer function estimates that were developed and used traditionally in areas of sound, motion, and vibration studies where random signal sequences of audio frequencies and below were studied. The application of SDE’s to High Voltage Impulse Testing and Harmonic Characterization of Power

Apparatus using a series of tailored pulses was initially developed by NEETRAC about twenty years ago [4,5]. The application of spectral density estimates for off-line and on-line detection of power transformer winding deformation has been developed and made possible by the recent emergence of high quality low cost digitizers, faster and more powerful computers, and new digital computational methods.

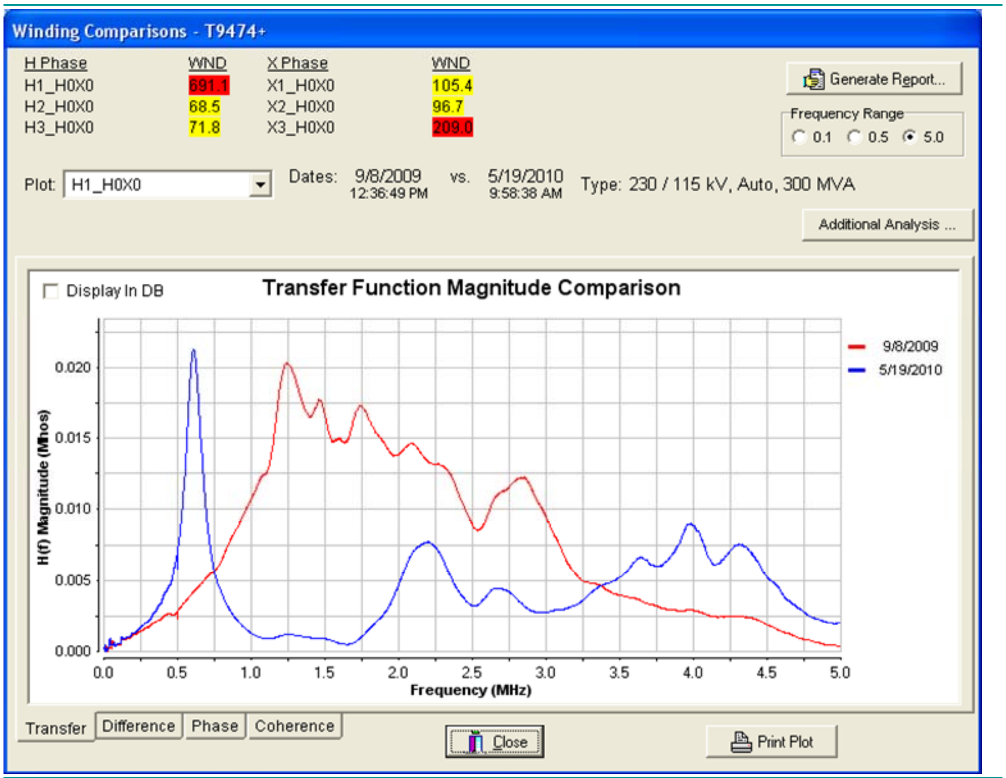
The use of SDE's for winding transfer functions provide the following unique benefits over traditional methods:

- The effects of noise are reduced to produce a higher test frequency bandwidth.
- Single phase data can be isolated from multiple phase composite data. For example, the single phase neutral components can be extracted for windings with all three phases in one tank having one neutral bushing.
- Random input data is used with varying magnitude and frequency parameters. A coherence function is used in software to evaluate the linearity and usefulness of the transient input waveforms to perform viable transfer functions.

End-of-Life PdM Indicator

One of the benefits of OLFRA is the contribution to predictive maintenance or condition assessment of windings near transformer end-of-life. As the available fault currents continue to increase and the average age of transformers continues to increase and as time scheduled periodic maintenance decreases, it becomes more important to accurately determine the condition of transformer windings and insulation on-line before imminent failure.

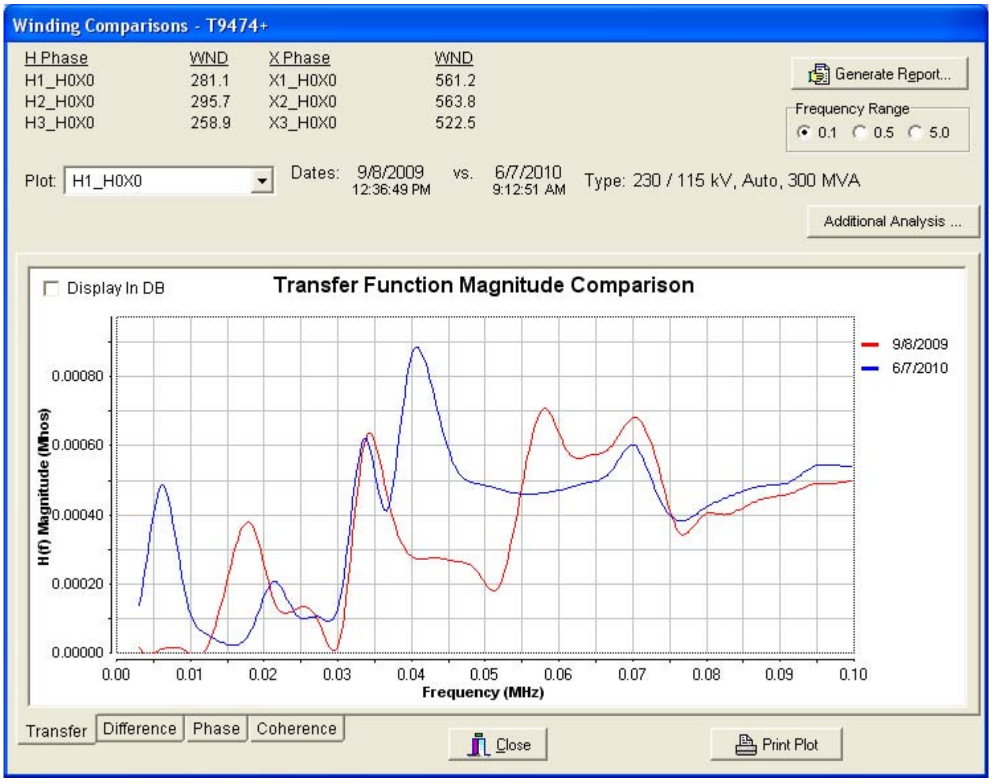
Traditionally, winding FRA has only been available as an off-line test and the evidence that significant winding deformation can be determined from an OLFRA test actually comes from an extension of off-line testing. The case presented is a 41 year old Westinghouse shell form transformer that was taken out of service for the installation of OLFRA. But the off-line FRA measurements taken indicated a significant change in the H1 winding since the last FRA test over 8 months prior. The transformer is located in a high fault current location where the frequency of through-faults is also high. The on-line DGA was good and the water content was low. The only reason the transformer was taken out of service was to install OLFRA equipment. However, an in-tank inspection revealed some very loose blocking between the phase windings. The upper blocks were available for manual inspection. The inspector noted that the very loose blocks indicated both horizontal and vertical movement by hand. The high frequency difference in the H1 winding off-line FRA is shown in **Figure 6**.



41 year old Westinghouse shell form after through-fault damage
High Frequency Changes from Off-line Testing
Figure 6

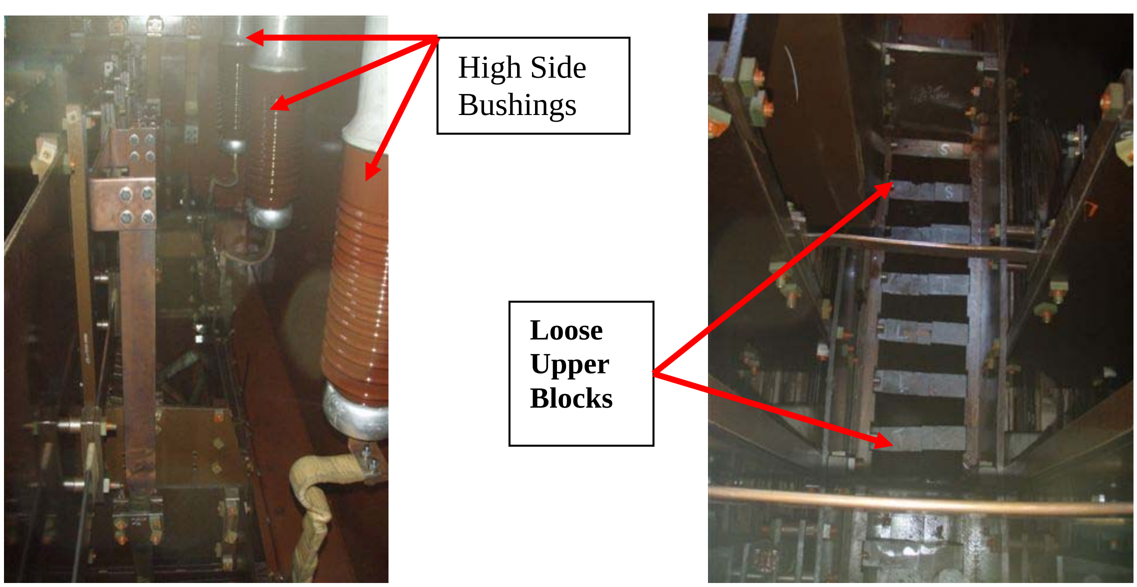
Differences in frequencies above 500 kHz have traditionally been indicators of damaged lead blocking on entrance to winding, high resistance connection to winding static shield, and winding overall looseness. In this case, extreme winding looseness is indicated by inspection.

Figure 7 shows the low frequency changes below 100 kHz over the 8 month period. These low frequency changes usually indicate bulk winding or disk movement. The larger the bulk that moves the lower the indicating frequency. The lowest frequencies up to 10 to 20 kHz are usually affected by the difference in residual magnetism in the core between tests but can also indicate core structural problems. The sound and vibration of the energized transformer were considered normal, so no core or lamination problems were indicated.



41 year old Westinghouse shell form after through-fault damage
Low Frequency Changes From Off-line Testing
Figure 7

See **Figure 8** for a picture of the upper blocks that were available for manual inspection.



Left shows top of all 3 phases with high side bushings on right
Right shows loose upper blocking between A and B phases
Figure 8

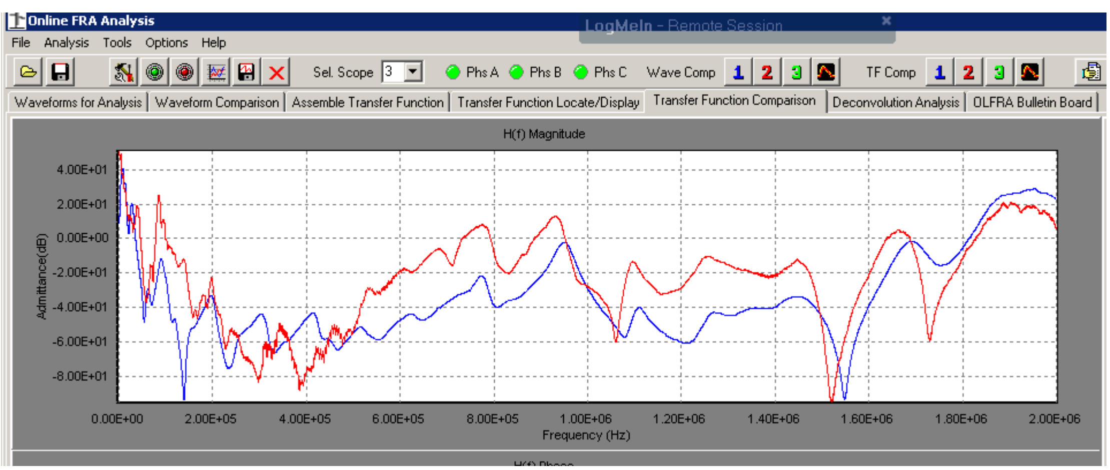
Three of the upper blocks were considered by the inspector as tight…could not move vertically or horizontally by hand. Two of the blocks were considered loose…could wiggle vertically but not horizontally. Two of the blocks were considered very loose…could wiggle blocks both vertically and horizontally. Each block was labeled accordingly for future reference.

It is very likely that this transformer withstood through-faults at this substation location between 9/8/2009 and 6/7/2010 to cause FRA (and winding) change. The off-line power factor tests revealed oil contamination so the oil was processed.

The transformer was re-energized temporarily but the unit is scheduled for replacement at this high fault location in 2011 due to extreme winding looseness. This type of shell form winding does not lend itself to normal methods of block tightening and the process was not attempted. We will show in the next section that the OLFRA method can indicate for this same type of winding looseness.

Off-line vs. On-line with OLFRA Equipment

An off-line FRA test with the neutral attached is normally performed as a baseline test to compare initial on-line results or as a comparison if the transformer is removed from service for some reason. The OLFRA with off-line pulses (baseline test) versus on-line test with on-line pulses for a 230 / 115 kV, 300 MVA, 10 year old auto is shown in **Figure 9**. The period of time for the collection and selection of usable OLFRA data is 6 months in this example.



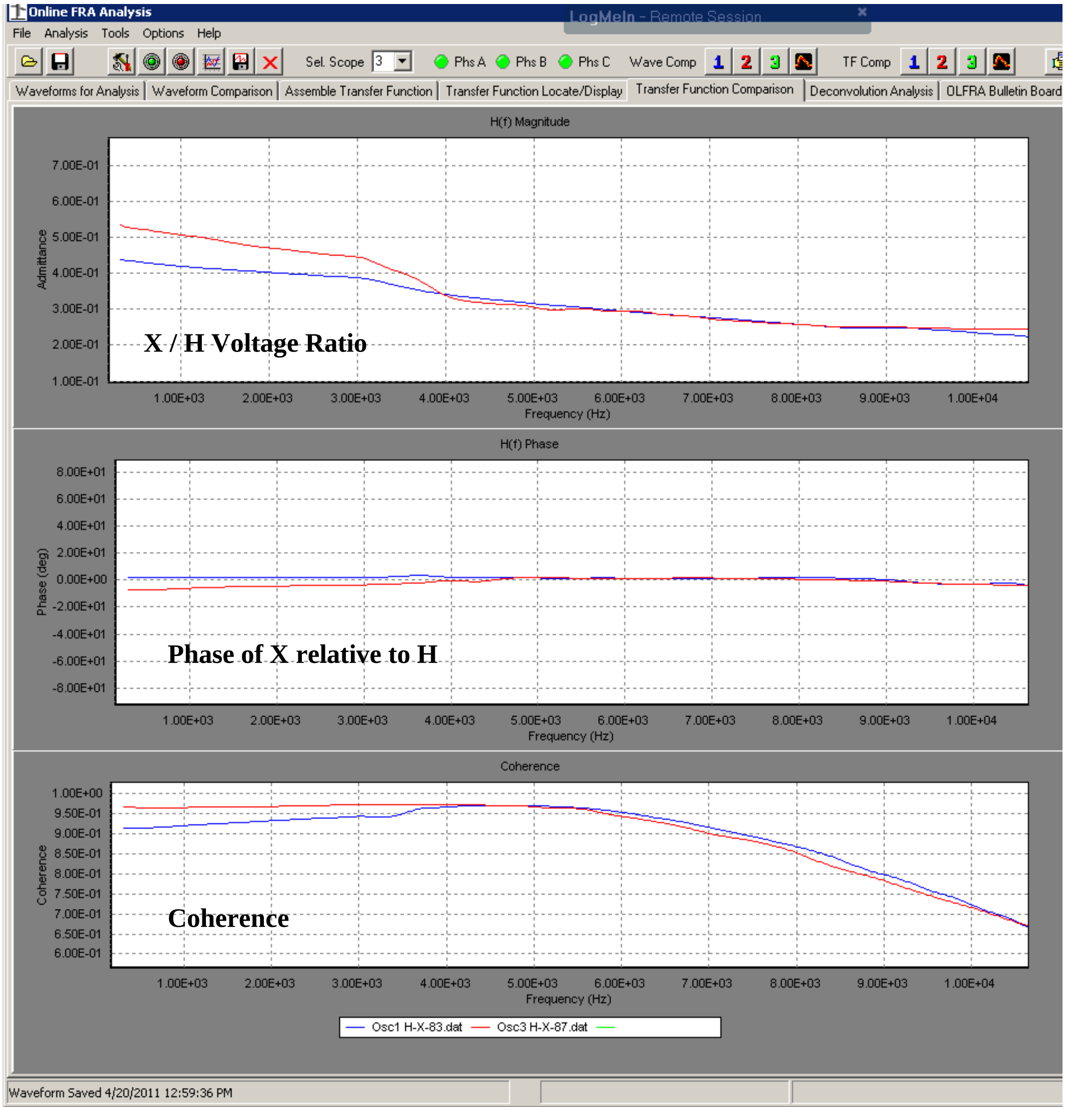
X1-N Off-line FRA (blue curve) with OLFRA Equipment vs.
X1-N On-line FRA (red curve) with OLFRA Equipment
Figure 9

Magnitude differences up to about 500 kHz are somewhat different because of in-service connections to bushings. For example, the impedance across the H winding affects the low frequency response of the X winding on the same phase. Remember that un-tested terminals are usually open for off-line FRA testing. The curve similarity is good from 500 kHz to 2 MHz. The shift to the left of the on-line (red) response is due to higher transformer winding temperatures for the on-line data. **Figure 9** illustrates a good verification of the OLFRA method using normal power system transients for input test data.

Low Frequency Winding Voltage Ratio vs. Frequency

One of the data sets available with the OLFRA is a voltage ratio from high-to-low and low-to-high voltage windings. An example of this data is given in **Figure 10**. This is the H to X winding OLFRA on-line test result for a 230 / 115 kV, 300 MVA, 10 year old auto with 6 months of on-line transients available. **In Figure 10**, the upper graph is the voltage ratio for the X winding output divided by the H winding input. The middle graph is the phase shift vs. frequency for X relative to H and the bottom graph is the coherence function calculation that indicates the data linearity across the frequency band.

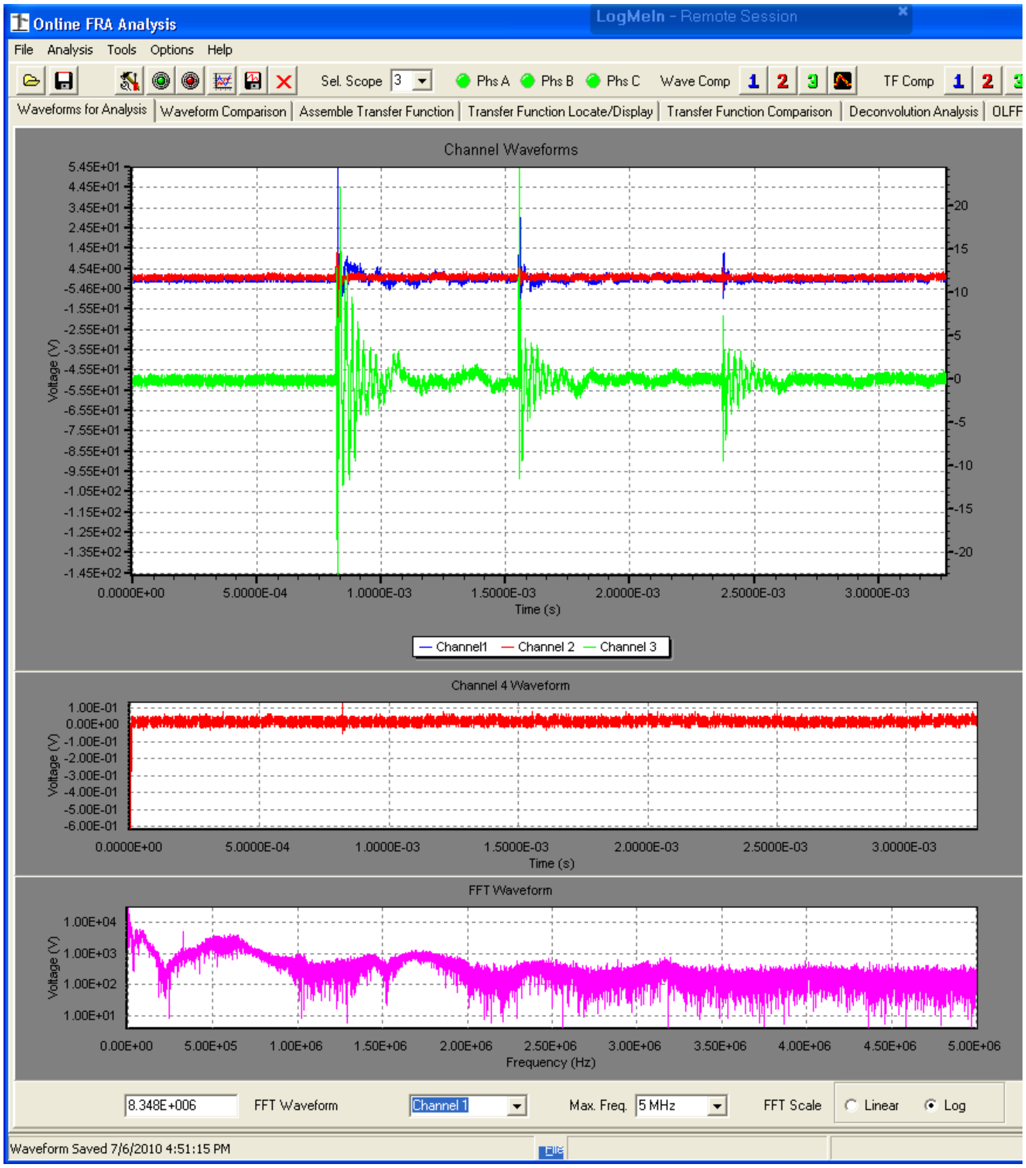
Note that for 300 Hz (first data point) the X magnitude is about ½ of the H magnitude which it should be for a 230 to 115 kV winding ratio. The phase changes only a few degrees for these frequencies and the coherence (data linearity) is very good (> 0.9) up through 7 kHz. This type of frequency measurement should provide good model information for EMTP programs and the like. This data can also be used to calculate the 230 kV and 115 kV bus steady state 60 Hz harmonic voltages.



Voltage Ratios: X1 divided by H1 and X3 divided by H3 are shown above
300 Hz to 10 kHz bandwidth with linear scaling
Figure 10

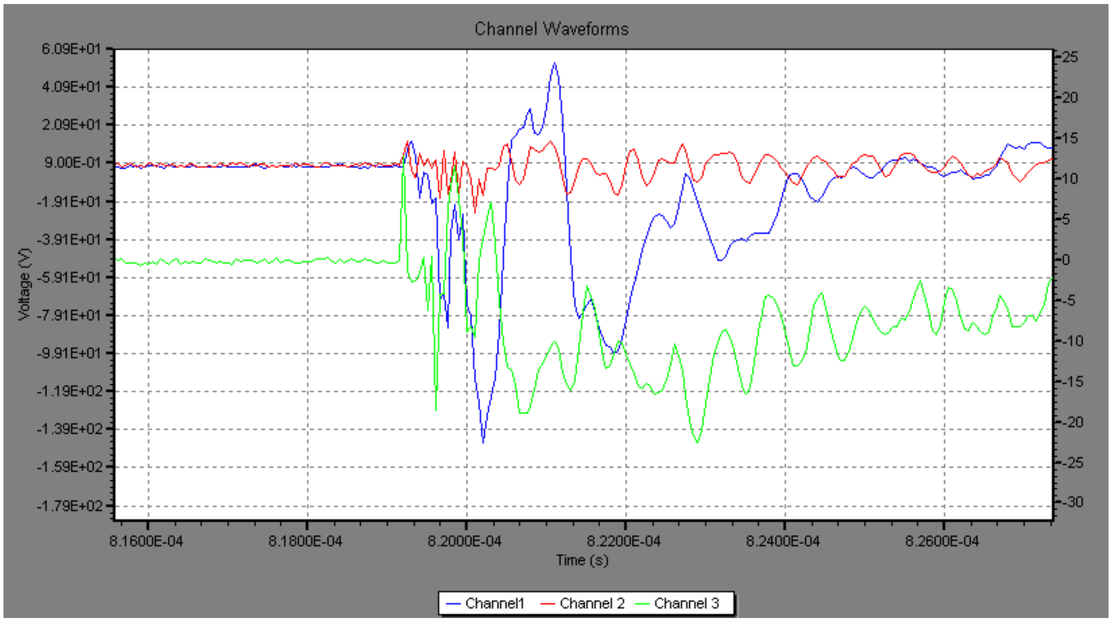
OLFRA Operates as a High Voltage Wide Bandwidth Transient Recorder
Recording the high voltage transients on the buses connected to the OLFRA equipped transformer is part of the on-going OLFRA process. These transients are the data base to select data for the OLFRA technique.

An example of the pre-strike of a 230kV, SF6 PCB on energizing a 230kV, 180MVAR, capacitor bank is shown in **Figure 11**. The transients are recorded on the OLFRA equipment of a nearby 230/ 115 kV, 300 MVA, auto-transformer. The top trace is the magnitude vs. time overlay of the H2 bushing tap, the X2 bushing tap, & the Neutral bushing waveforms for the transformer. The waveforms are sampled at 12 bit, 20MHz w/ 64K records. The 60 Hz is filtered out to increase transient dynamic range of measurement. The bottom purple graph is the FFT of the H2 tap waveform that indicates frequency energy well into the MHz range. The FFT full scale is 5MHz.



Transient records of the 230kV SF6 PCB prestrike transients on energizing the 230 kV cap bank near the transformer with OLFRA equipment
Figure 11

A zoom-in on the first burst which has the highest amplitude is shown in **Figure 12**. This 230 kV capacitor bank has an SF6 breaker with closing resistors and neutral current limiting inductors. There are also TRV capacitors on the 230 kV bus less than 300 feet away. And it is noted that the maximum prestrike breaker contact transient is about 3 KV on **Figure 12**. The low magnitude recorded transients indicate that the surge protective equipment is working as designed.



Zoom-in on first burst in Figure 11

Blue = H2 bushing tap. (Bushing input max. approx. 3kV pk.) Red = X2 bushing tap. Green = Neutral bushing & represents pulse travel through H2 transformer winding / insulation combination from H2 to neutral. Horzontal Scale = 2 uSec / big division

Figure 12

Conclusions

- The OLFRA equipment is installed in a small cabinet on the side of the transformer. OLFRA, OLRPF, & PD can exist simultaneously on the same bushing tap.
- The patented method reduces the affects of noise to produce a higher test bandwidth. The technique also can isolate single phase data from three phase composite neutral data. And the patented algorithms can evaluate the linearity & usefulness of the transient input waveforms to perform viable transfer functions.
- A validation case is presented to demonstrate that OLFRA should detect transformer end-of-life winding deformation.
- The OLFRA technology is validated by comparing manual off-line input pulse results to on-line results using normal system transients.
- A winding voltage ratio versus frequency feature is demonstrated from 300 Hz to 10 KHz.
- The OLFRA bus transient recording feature shows the normal closing transients of a 230 kV capacitor bank with closing resistors and current limiting reactors in the neutral of the capacitor bank.

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Biographies

Larry Coffeen is a Senior Research Engineer for NEETRAC, a research organization with a membership of power equipment manufacturers and electric utilities. NEETRAC is also a part of the school of Electrical and Computer Engineering at the Georgia Institute of Technology. Larry's current work includes the development of test techniques and test equipment to perform ON-line transformer, CCVT, and power line carrier trap frequency response analysis.

Before joining NEETRAC, Larry was employed for 29 years by Georgia Power Company. As a Senior Test Engineer, he performed Transmission Substation Testing and High Voltage Laboratory test work. After the formation of NEETRAC in 1996, Larry continued to work in the High Voltage Laboratory and develop new field test technology for substation equipment.

Larry received a Bachelor of Electrical Engineering degree from Georgia TECH in 1970. He is a senior member of IEEE and a Member of the IEEE, PES, PSIM (Power System Instrumentation & Measurements) Committee since 1987. Larry contributed actively to IEEE Std 4-1995, "IEEE Standard Techniques for High Voltage Testing" as an active member of the High Voltage Testing Techniques subcommittee of PSIM. He is contributing to the current IEEE Std 4-1995 revision as a corresponding member of HVTT PSIM. Larry has been a contributing member of the IEEE, Transformers Committee, FRA Guide Working Group from 2003 to the present.

Larry holds five U.S. patents relating to power transformer FRA testing, MOV lightning arrester and polymer insulator field test methods.

Jim McBride received a Bachelor of Electrical Engineering degree from Georgia Institute of Technology in 1988. He has worked in power system research and development for 25 years. Jim has worked extensively with calibration, high voltage testing, and frequency response testing. His areas of expertise include data acquisition, software development, and high voltage testing. Jim has worked with many predictive maintenance and testing techniques used for evaluating power equipment. He is currently president of JMX Services, Inc., which is a provider of monitoring/testing products and services for the power industry.

Jim has been an IEEE PES member since 1990 and was formerly secretary of the PSIM Committee. He is an active member of the High Voltage Testing Techniques Sub-committee of the PSIM Committee. He is also an active member of several working groups within the Transformers Committee.