Initial Development of EHV Bus Transient Voltage Measurement: An Addition to On-line Transformer FRA

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EPRI Substation Equipment Diagnostics Conference
Orlando, FL
March 2008

Abstract

The evidence is growing world wide that EHV level transients caused by fast switching devices are breaking down insulations in power circuit breakers and transformers. The normal substation devices such as capacitor coupled voltage transformers, potential transformers, and equipment bushings do a good job at power frequency, but all have significant limitations (resonant frequencies in the ratio versus frequency) for measuring transients with higher frequency content [5].

A measurement technique is under development at the Southern Company (SoCo) to determine the magnitude and characteristic shape of high voltage transients on the 230 kV and 500 kV bus in Georgia Power's O'Hara Substation. This is in conjunction with the continuing on-line FRA (frequency response analysis) project on the 500 / 230 kV auto-transformer at the O'Hara Substation [1,2,3].

The same bushing tap source for the on-line FRA is used to calculate the magnitude and wave shape of the transients at the 230 and 500 kV transformer bushing inputs. A laboratory grade wide bandwidth voltage divider is erected in close proximity to the phase one 230 kV transformer bushing to validate the transient calculations from the FRA software. The de-convolution software is not yet complete to produce corrected time domain transient data from the bushing tap information, but comparisons can be made from the raw time domain data.

This paper shows a comparison of transients from the bushing taps and the wideband voltage divider. The paper also shows that transients of a relatively high frequency content are available on an EHV bus and these same transients travel through the windings to allow the on-line computation of a frequency response analysis (FRA) for the perspective winding. The transients generated from de-energizing 950 ft. of 500 kV bus and from low level lightning outside the substation are discussed.

Voltage Divider Installation

An outdoor laboratory grade wideband voltage divider was chosen for installation near the 3 phase, 2000 MVA, 500 / 230 kV auto-transformer, phase 1, to record and analyze actual transients on the 230 kV bus. This divider will ultimately validate the software corrections to the transients recorded from the transformer bushing taps so that accurate EHV transient records can be made form the bushing taps without the presence of a voltage divider. The bushing tap data must be corrected to represent the bus data since the bushing has its own transfer function with its characteristic resonances that influence the measurement.

The divider was provided by Bonneville Power Administration (BPA) and has a specification of dc to 1 megahertz with a1% ratio accuracy up to 400 kV dc and 320 kV rms ac. The divider is installed near the X1 bushing which has a nominal 132 kV of phase-to-ground voltage. See Figure 1 for the divider installation.

BPA Divider Installation @ GA Power
Figure 1

Divider Withstand & Calibration Tests

The transportable divider was first erected in the NEETRAC high voltage laboratory for ac and impulse withstand testing along with ratio calibration according to IEEE Std. 4 – 1995 [4]. The tests performed were:

1. Ac 60 Hz ratio from 40 kV to 300 kV rms with 75,007:1 result
2. Partial discharge @ 300 kV with 2 PC result
3. Impulse withstand of 3+ & 3-, 1 MV lightning impulses with 72,973:1 ratio compared to the laboratory 2.1 MV impulse divider
4. Impulse time domain calibration from 45 to 200 kV with laboratory reference voltage divider. 76,015:1 magnitude ratio with good comparison of impulse front & tail time characteristics. See Figure 2 for divider comparisons. Note that the time delay of the BPA divider waveform is due to the extra 100 ft. of cable length from the low voltage arm needed for the substation application.

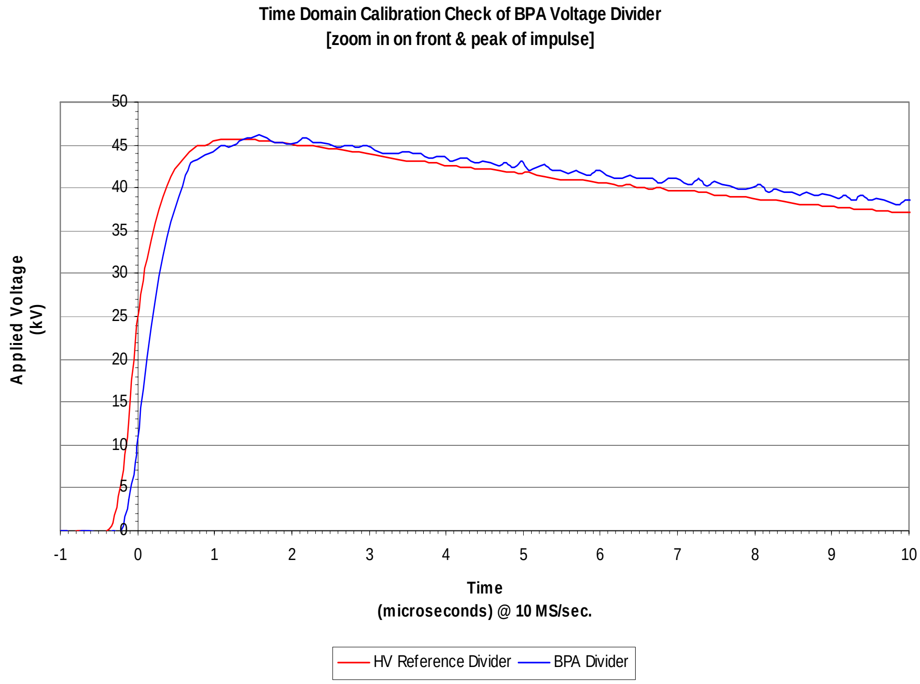
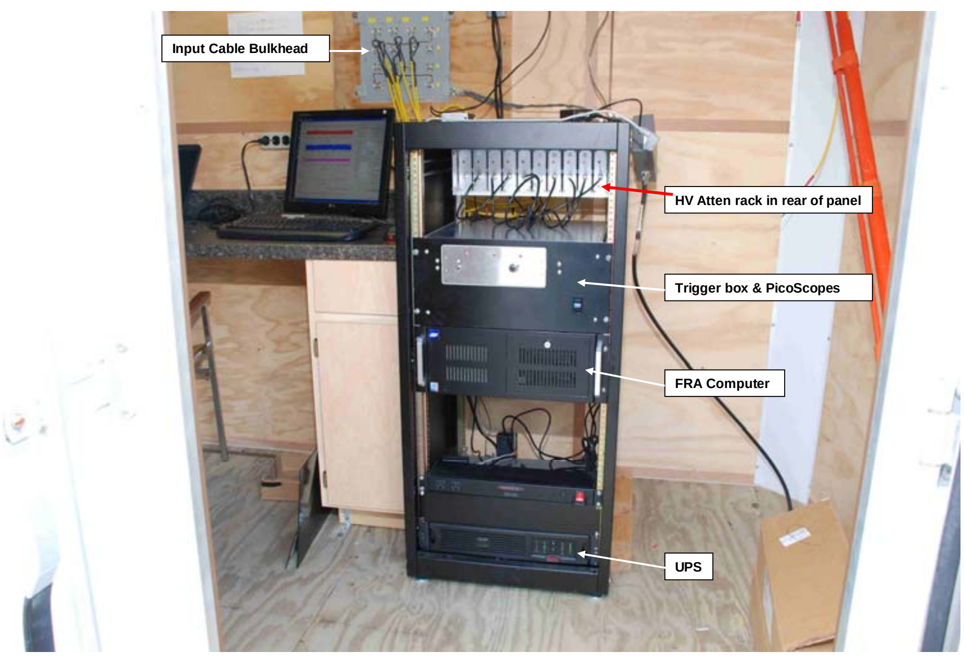


Figure 2

Transient Recording & FRA Equipment

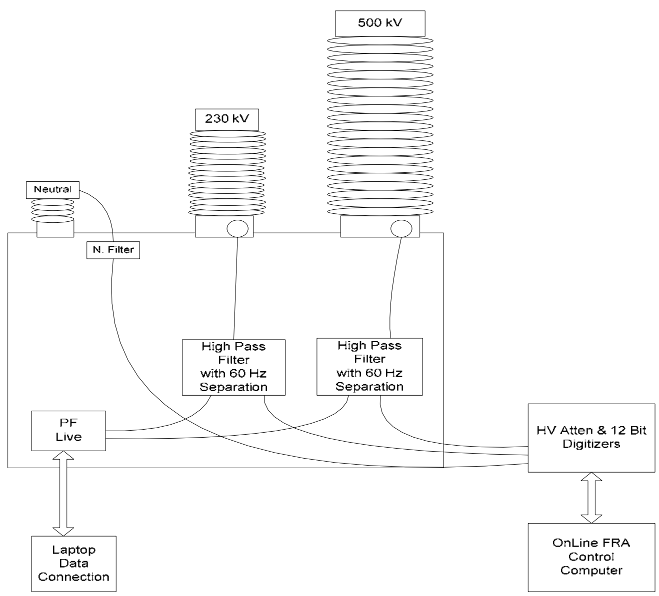
The transient recording equipment for the BPA divider was added to the existing FRA equipment trailer located near phase 3 of the 500 / 230 kV auto-transformer. See Figure 3 for the equipment location and Figure 4 for the equipment description in the trailer. The FRA & HV transient recording equipment is nearing the end of re-packaging to a smaller format to allow ease of transportation from substation to substation as the need arises. EPRI has continued to sponsor the re-packaging of the equipment towards commercialization [2].

On-line FRA & Transient Recording Equipment Location
Figure 3



Downsized Equipment in Trailer
Figure 4

Equipment Interface to Power System
The equipment interface for the EHV bus transient recorder is designed to use the same bushing taps as used for the on-line FRA and bushing relative power factor. The EHV transient recorder, the on-line FRA diagnostics, and the bushing relative power factor operate simultaneously on-line. The de-convolution software for the EHV transient recorder is not complete at this writing, but we can show the types of transients recorded to date that are useful for on-line FRA and demonstrate that an EHV bus can host transients of high frequency content. The EHV transient recorder, on-line FRA diagnostics, and relative bushing PF system layout is shown in Figure 5.



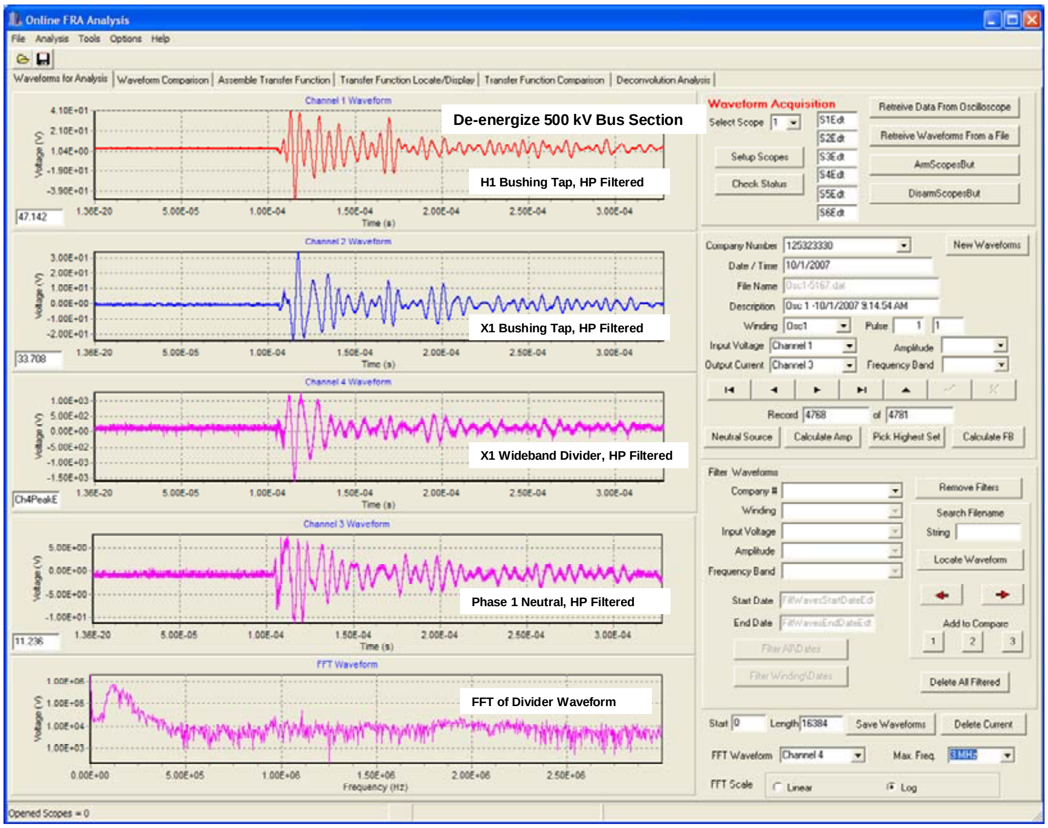
ON-Line System Layout
(a typical phase)

Figure 5

De-energizing 500 kV Bus Section
The high side of the 500 / 230 kV auto-transformer is a ring bus consisting of four 500 kV transmission lines. The 3 phase bus section for this ring bus, that was de-energized by a motorized disconnect switch, is 950 feet in length. The disconnect switch is located about 300 feet from the high side of the auto-transformer.

The wideband voltage divider output is recorded simultaneously with the outputs of the H, X, & Neutral bushing high pass filters for the phase 1 auto-transformer. The high pass filters are maximally flat, linear phase, 3^{rd} order filters to minimize the large 60 hertz components in order to maximize the dynamic recording range of the high frequency transients.

Waveform Analysis
The waveform captures for de-energizing the 950 feet of adjacent 500 kV bus section are shown on the on-line FRA software window in Figure 6. These waveforms are triggered by the first transient from the opening switch to go above the trigger level of the recording equipment, so the waveforms presented may not reflect the highest level transients generated for this event. The intent was not to capture the highest transient magnitude levels but to show the frequency content of the transients on an EHV bus and their ability to travel through the transformer windings of a large power transformer.

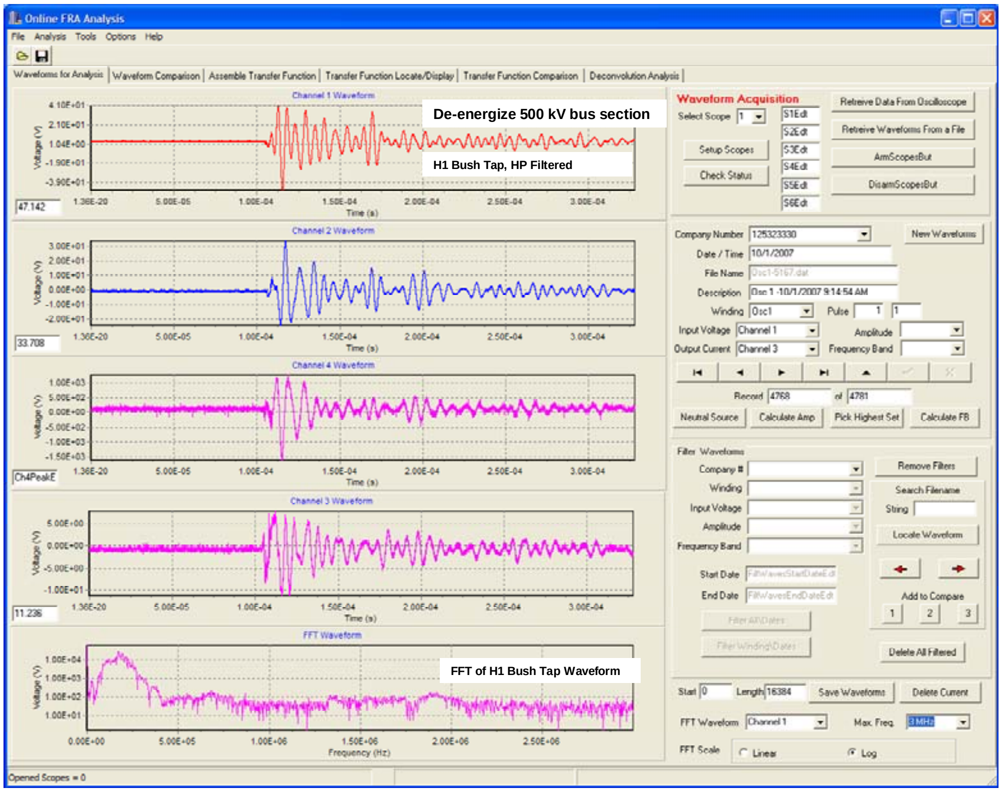


H1, X1, Neutral, & Divider Waveforms, & FFT of Divider Waveform
Figure 6

Observations:
The most dominant frequency for this on-line event is about 175 kHz at the H1 bushing tap (channel 1). A slightly lower frequency with a 2.7 kV peak-to-peak is recorded by the wideband divider next to the X1 transformer bushing (channel 4). The X1 bushing tap record (channel 2) is also similar to the wideband divider trace. The same dominant frequency can also be observed at the transformer neutral (channel 3). So the "ringing" observed from the H1 and X1 bushing taps and the neutral bushing are not a result of the bushing characteristics but are the actual 500 kV-through H1 winding-through X1 winding- to phase 1 neutral response to the opening 500 kV switch. We also know from performing an off-line FRA of the bushings with their associated filters and cabling that the H and X bushing responses are flat near 175 kHz, so it is reasonable to expect the X1 bushing tap trace to be similar to the wideband divider waveform at this frequency.

We also observe from the FFT of the divider waveform at the bottom of Figure 6 that the FFT voltage is considerably above the baseline for frequencies below 500 kHz and slightly above the baseline for frequencies in the 1MHz to 2MHz region. This is also an indicator that some of the high frequencies are passing through the transformer windings.

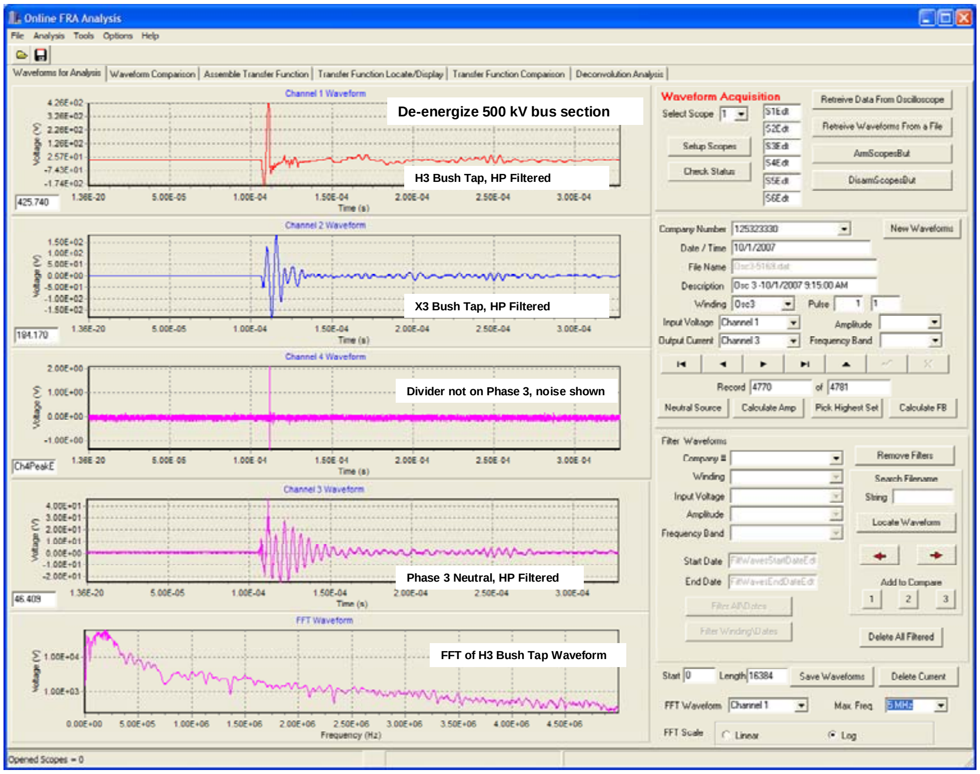
Figure 7 is the same as Figure 6 with the exception that the bottom trace is an FFT of the H1 bushing tap waveform which also shows frequencies higher than the baseline up to about 2 MHz.



H1, X1, Neutral, & Divider Waveforms, and FFT of H1 Bushing Tap
Figure 7

Figure 8 shows the waveform captures for phase 3. In this case, the transient recorded from the 500 kV switch opening is much larger in magnitude with higher broad band frequency content. The numbers inserted to the left of each of the waveform graphs indicate the peak voltage recorded for the respective waveform record. The H3 trace of Figure 8 indicates a peak of 426 volts compared to the 47 volts peak of the H1 trace shown in Figures 6 & 7.

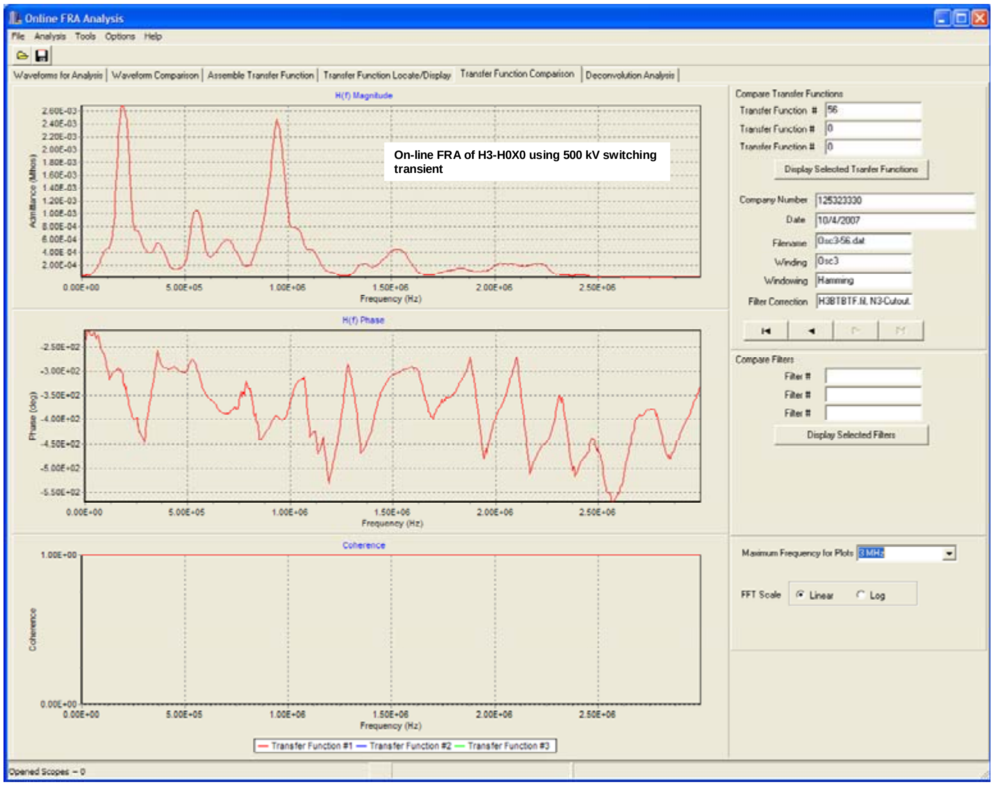
The H3 record of Figure 8 appears to be one of the higher voltage re-strikes on the switch opening. This open air re-strike offers a fast transition and an estimated 30 kV peak at the top of the H3 bushing which gives an excellent broad band pulse to perform on-line FRA for the H3 winding.



H3, X3, Neutral, and FFT of H3 Bushing Tap Waveform
Figure 8

On-line FRA Measurement

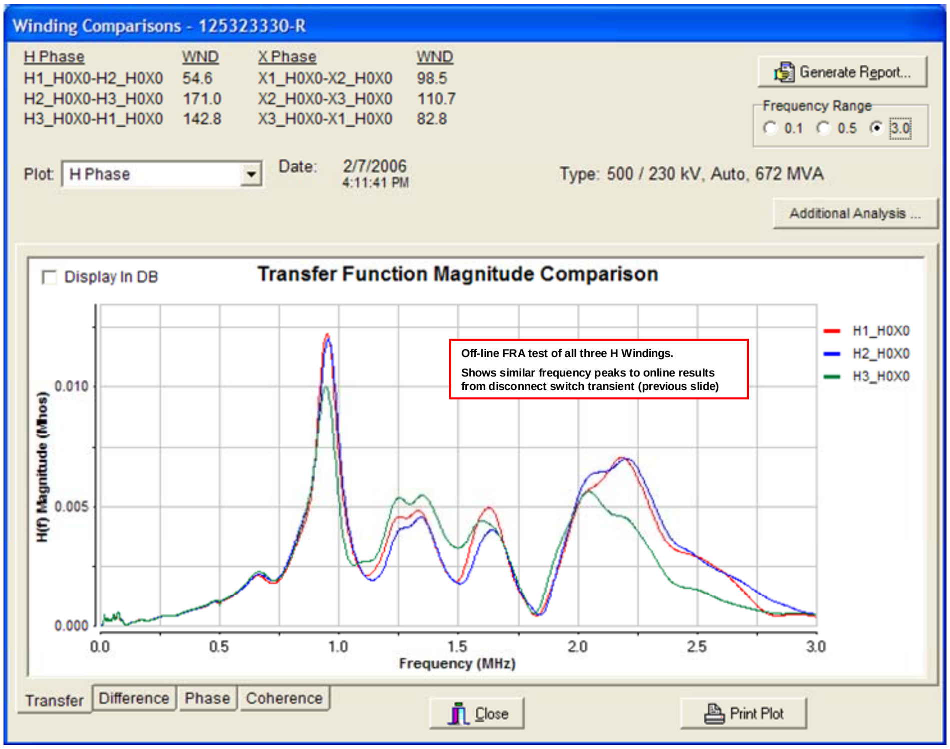
The on-line FRA for the H3 winding is shown in Figure 9. As expected from the time domain waveform analysis, the highest resonant peak for the transfer admittance magnitude trace is around 175 kHz for the frequency response analysis as shown in the top trace of Figure 9. There are also additional peaks in the 500 kHz to 2.0 MHz region which also correlate with FFT voltages above the baseline for the divider and bushing tap waveforms of Figures 6 & 7. This also indicates the sensitivity and accuracy of the FRA technique as compared to analyzing raw time domain waveforms. The low end cutoff for the on-line FRA analysis is about 60 kHz to prevent large 60 Hz and harmonics of same from using up the dynamic range of measurement for the higher frequencies.



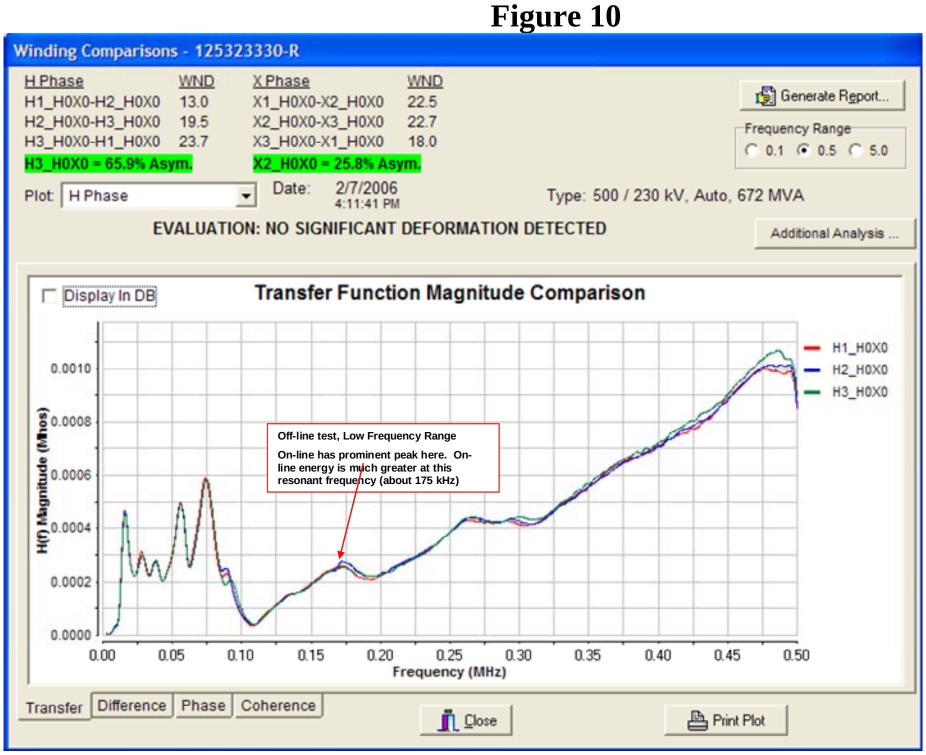
On-line FRA of H3 Winding Using 500 kV Switching Transient
Figure 9

Off-line FRA Measurement Comparison

The frequency of the resonant peaks and the characteristic magnitude shapes for on-line versus off-line can be compared for the frequency range of about 700 kHz to 2.5 MHz. See Figure 10 to compare off-line FRA. The 175 kHz peak shows up as a much lower level on the off-line test because the energy input off-line, at this frequency, is much smaller than for on-line. See Figure 11. The 175 kHz is a natural frequency of the system with lots of energy for the local 500 kV bus and transformer windings combined, and therefore produce a high peak for the on-line FRA.



Off-line FRA of H3, H2, & H1 Displaying 3.0 MHz Range
Figure 10



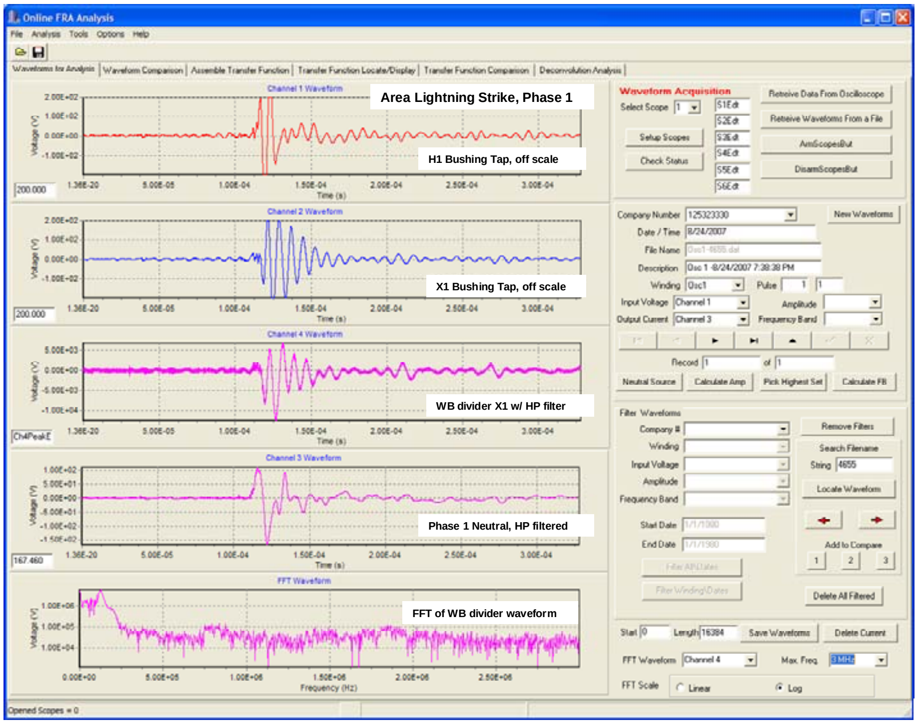
Zoom-in Off-line FRA of H3, H2, & H1 Displaying 500 kHz Range
Figure 11

Lightning Waveforms

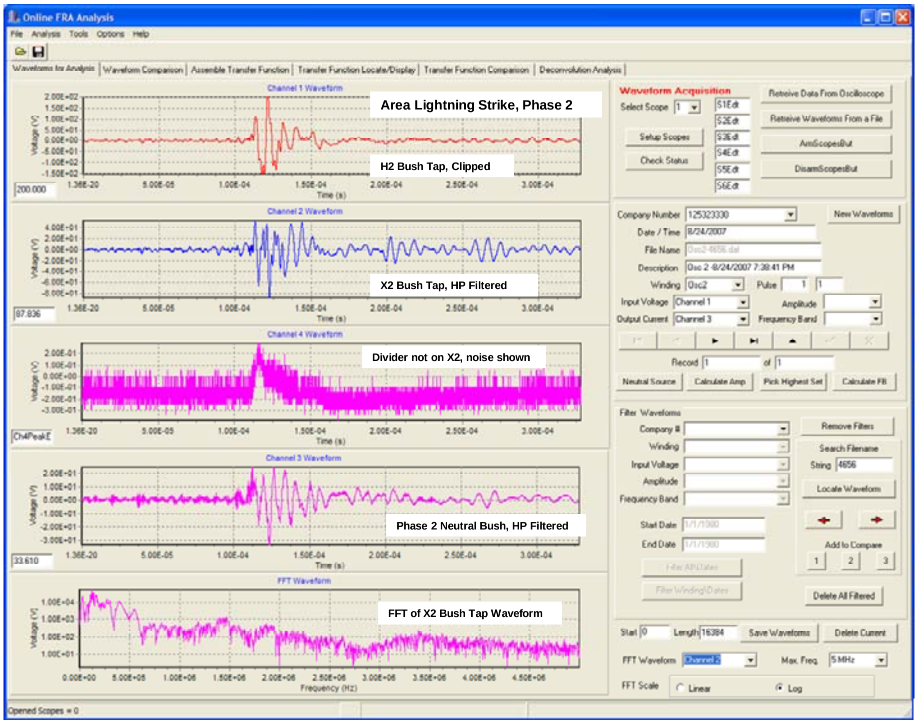
The local area lightning is a good source of on-line pulses to perform on-line FRA. For the most part, these pulses originate some distance from the substation due to induced or indirect lightning strikes to a transmission line. Most of these pulses are in the one to a few tens of kV peak magnitude on arrival to the test transformer.

Figure 12 shows the waveform captures for an area lightning event which happened while the author was sitting in front of the on-line FRA equipment during a small thunder storm. Unfortunately, both the H1 and X1 bushing tap waveform magnitudes railed the attenuator settings at that point, but the waveform for the wideband divider was preserved to show about an 18 kV peak-to-peak value for the X1 bushing input. The FFT of the divider waveform is shown at the bottom of the Figure 12 which indicates high frequency voltages present.

In addition, it is known that the source of the lightning pulses are from the 500 kV system because the X2 waveform of Figure 13 is much smaller in magnitude than the H2 waveform in the same figure, and the phase 1 and phase 2 captures were made simultaneously. The FFT of the X2 bushing tap waveform at the bottom of figure 13 also shows high frequency voltages present.



On-line Lightning Pulse Captures, Phase 1
Figure 12



On-line Lightning Pulse Captures, Phase 2
Figure 13

Switching Transient Observations to Date

- **500 / 230 kV systems can have transients present with frequency content into the MHz region.**
- **These transients can be generated by local switching and / or lightning.**
- **High frequencies can pass through a 500 / 230 kV auto with significant energy content to excite resonant frequencies in the windings sufficient for on-line FRA.**

Future

- **Continue developing an addition to the on-line FRA software to database corrected EHV transients**

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