A Most Unusual Event Analysis

1. Introduction:

On Saturday night 2/25/2017 at 20:51:15 a transformer differential relay associated with the Sheffield wind farm 115KV/34.5KV GSU transformer misoperated resulting in the tripping of the 115KV interconnection and wind farm collector 34.5KV circuit breakers. A severe lightning storm was in progress at the time with a trip/reclose of a nearby 115KV transmission line occurring 8 seconds prior. The transformer and wind farm were returned to service after an Operations Analysis had determined that the transformer differential relay had misoperated.

A review of area DFR records indicated that a large DC current pulse flowed across the Northern VT 115KV, 46KV and 34.5KV transmission systems with the highest flow occurring on the Sheffield T1 115KV/34.5KV/13.8KV grounded wye transformer primary windings. The following action has been taken;

a. The Sheffield K47 and KT1 115KV circuit breakers tripped during the event and had sustained DC current flow while the contacts were open. The breakers were inspected and no unusual contact wear was noted.
b. The Sheffield T1 transformer testing revealed no abnormal conditions from this event.
c. The Sheffield 87T1S transformer differential relay operated incorrectly due to the high DC current flow that it experienced and not due to any other design or setting issue.
d. The K60 shield wires at the HVDC line crossing were removed. Physical evidence indicates that the HVDC line to K60 shield wire fault has occurred six times in the past. A metallurgical analysis of the shield wire arc marks indicated that a self-extinguishing arc between the shield wire and a -450KV conductor occurred.

Summary and Recommendations

On 2/25/17 at 20:51:15, thousands of amperes of DC ground current flowed through the northern Vermont 115KV and 34.5KV systems with the greatest flow occurring on the Sheffield T1 30MVA 115KV/34.5KV three winding transformer with approximately 5200A flowing though the H0 bushing to ground. The Sheffield 87T1S secondary transformer differential relay operated incorrectly resulting in the opening of Sheffield K47 and KT1 for the DC current event.

The flow of DC current in an AC power system is a very unusual event that could have catastrophic consequences if the DC current is of sufficient magnitude and duration.

An investigation into the cause of the DC current flow determined that the Phase II HVDC -450KV pole faulted to the K60 shield wire at the line crossing in Waterford VT and that the fault self-extinguished.

The HVDC line operated normally during this event and no that abnormal conditions or alarms were recorded. A review of line clearances at the fault location indicates that the DC line conductor/ K60 Shield wire clearances were marginal during certain weather and loading conditions. The K60 shield wires at the HVDC/K60 line crossing were removed which eliminates the possibility of this event happening again.

Physical evidence indicates that the HVDC line to K60 shield wire fault has occurred six times. A metallurgic examination of the shield wire arc marks indicated that the marks were consistent with a self-extinguishing arc with the shield wire acting as the anode.

A review of area DFR records has identified two prior events where DC current has flowed in Northern Vermont AC power system.

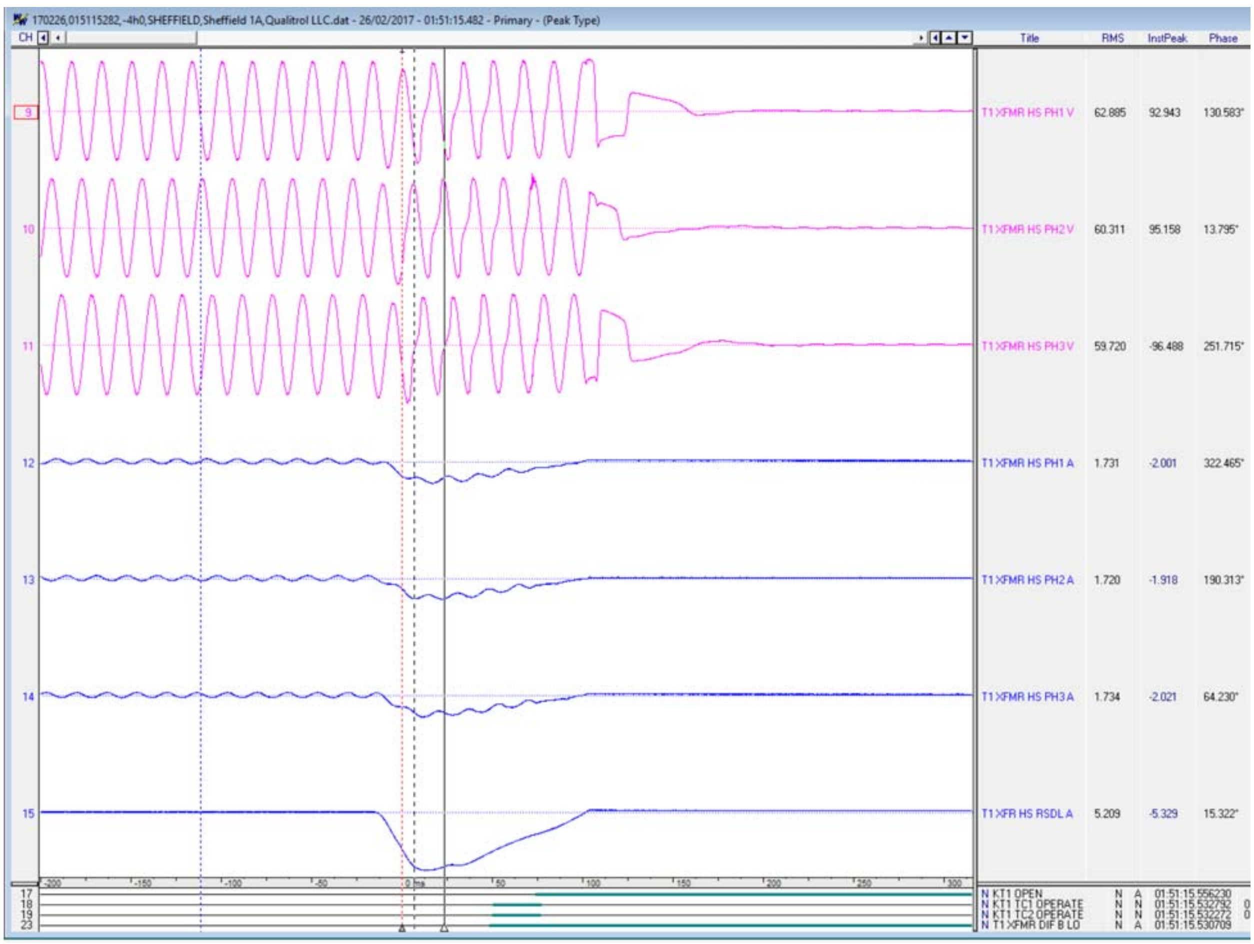
The Sheffield K47 and KT1 115KV circuit breakers tripped during the event and had sustained DC current flow while the contacts were open. The breakers were inspected and no unusual contact wear was noted.

The Sheffield T1 transformer testing revealed no abnormal conditions from this event.

The Sheffield 87T1S transformer differential relay operated incorrectly due to the high DC current flow that it experienced and not due to any other design or setting issue. The relay could be de-sensitized to the zero sequence DC current flow by connecting the CT's in delta and changing the settings. This is not required/recommended.

2. Detailed Analysis
    a. DC Current Flow

The DFR recording of the DC current pulse at Sheffield T1 is shown below. The duration of the DC current pulse was approximately 120 milliseconds with a linear decay starting ~50 ms after the pulse started. The DFR record below provides the Sheffield T1 115KV currents and voltages. The RMS quantities shown are KV and KA. The time/date noted is UTC time (EST = -5hr). The DC ground currents peaked at approximately 3I0 = 5200A DC, I_{Phase} = 1730A DC.



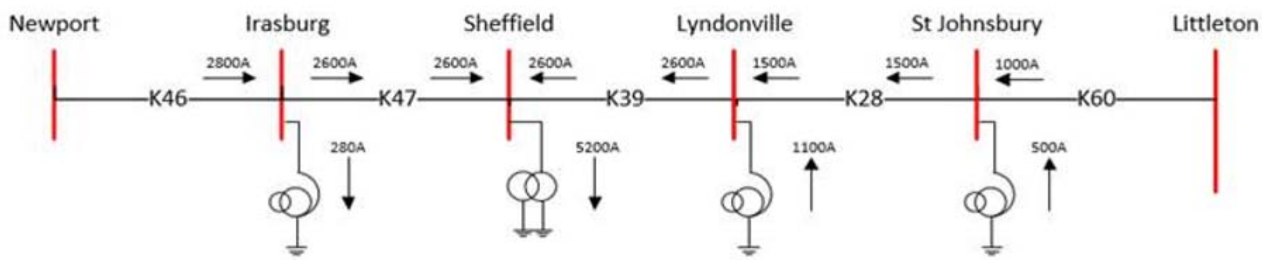
Sheffield T1 DC Current Pulse

DFR records indicate that significant DC ground current pulse flowed through the following transformers.:

1. Sheffield T1 115KV/34.5KV/13.8KV three winding transformer
2. Irasburg 115KV/46KV Autotransformer
3. Jay 115KV/46KV T1 Autotransformer
4. Jay 115KV/46KV T2 Autotransformer
5. Lyndonville 115KV/34.5KV T1 Autotransformer
6. Newport 115KV/46KV T1 Autotransformer
7. Newport 115KV/46KV T2 Autotransformer

8. St. Johnsbury 115KV/34.5KV Autotransformer

The flow of the DC current pulse on a portion of the 115KV system is shown below. The DC current obeyed KCL's entering & leaving all of the substations and the current flow appeared in the transformer tertiaries. DFR records for all of the above transformers are included in section 4 of this report.



Northern Vermont DC Current Path

The cause of the DC current low was suspected to be to an HVDC line fault with the HVDC fault current return path including the Northern Vermont AC transmission system. All other sources of DC current flow would be of much smaller magnitude and much longer duration (Geomagnetically Induced Currents) or of a very short duration (lightning). A search of the lightning data base indicated that a lightning strike had occurred in the vicinity of the Sheffield Substation at the exact time of the start of the DC current pulse. The lightning strike location suggested that the suspected HVDC line fault was at the K60 line crossing due to a lightning induced surge on the grounded K60 shield wire. Hydro Quebec and National Grid were contacted and they indicated that the Phase II HVDC operated normally during the event with no alarms or unusual events reported.

b. HVDC Line Fault Investigation

Detailed ground level photographs were taken of the shield wire and DC Pole conductors at all four K60 line shield wire crossings with particular attention to the crossing that appeared to be the closest and which exhibited audible corona. An examination of the photographs identified a shield wire anomaly at that location.

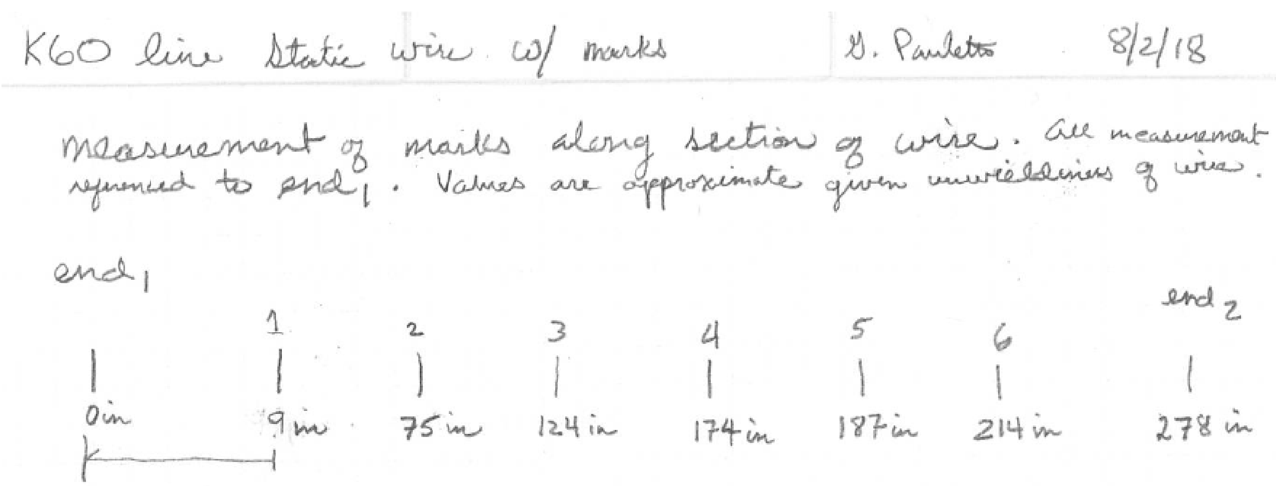
K60 Shield Wire Arc Mark

K60 – HVDC Line Crossing Fault Location

K60 Shield Wire Clearances

A review of DC line and the K60 line conductors and shield wires indicated that although the clearances meet NESC code under certain line operating conditions and weather cases, less than desirable clearance buffers exist and could have been as low as 10.4 feet at the crossing with the shield wire anomaly. Velco decided to remove the K60 shield wires at this crossing location in view of the minimal clearance that was there. This span would remain adequately protected from lightning via the DC shielding conductors. The shield wires were permanently removed and hand inspected. Shield wire surface anomalies were found at six locations, all in proximity to the highlighted HVDC negative pole crossing. The surface anomalies were all aligned on one side of the shield wire and were all roughly the same size.

K60 Shield Wire Arc Mark #5



c. Shield Wire Testing

Two sections of the static wire that included arc marks 1 & 3 were sent to a materials lab for analysis with no information provided on the origin of the samples. The materials lab concluded that the shield wire marks that were present were due to a localized thinning of the zinc galvanized layer and that no structural damage to the steel occurred which would be typical for exposure to an electrical arc. There were no significant differences in the composition of the material at the damaged spots from an undamaged remote spot on the wire. The cause of the corrosion could not be determined but there was no evidence of a manufacturing defect in the wire or evidence of a typical arc.

The origin of the shield wire samples and the suspected arcing of the shield wire to -450KV conductor were discussed with the metallurgist. The metallurgist concluded that the observed features of the shield wire localized corrosion could be produced by an arc of a short duration with the galvanized steel wire acting as the anode.

d. Theory of Flashover Incident

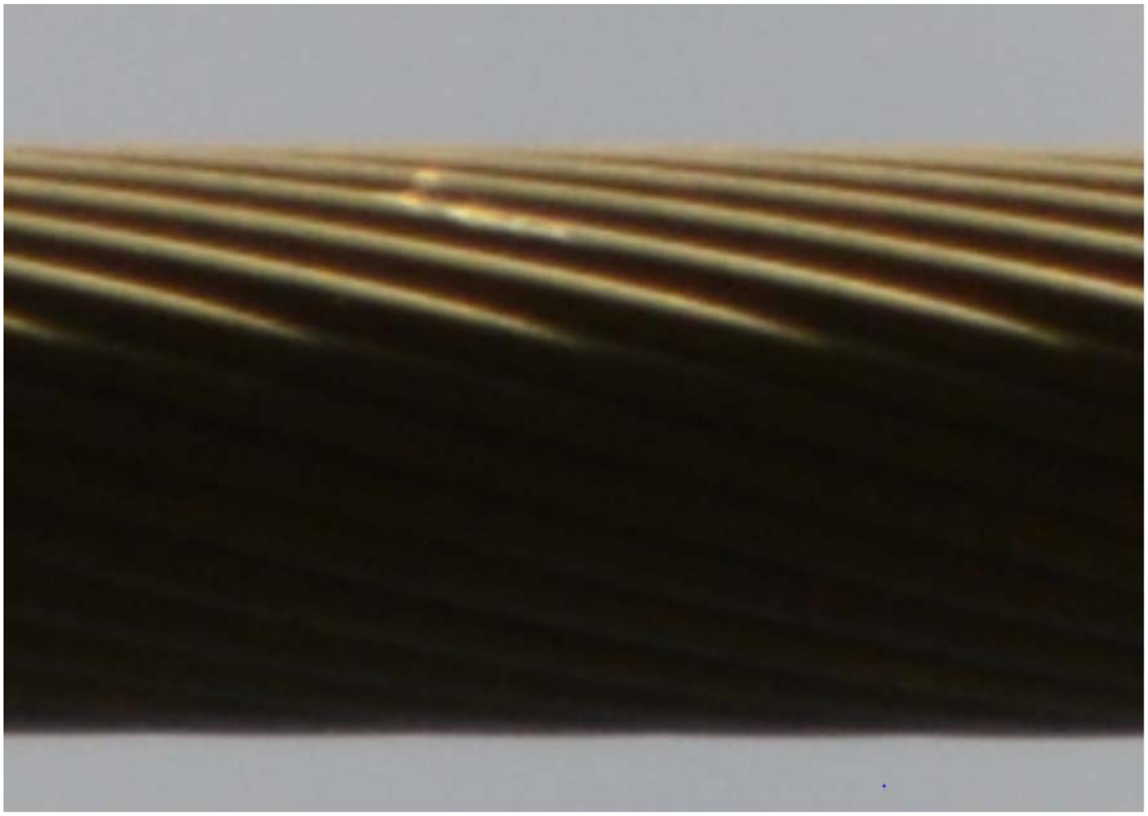
A review of electric arc physics indicated that for an electric arc to occur between two metal surfaces, the positive anode & negative cathode must reach their respective boiling points and release metal vapor for the arc plasma to form between these points. The temperatures of the anode and cathode are limited to the boiling point of the materials and the arc will be sustained only as long as there is a steady supply of positive ions from the anode and electrons from the cathode. The K60 shield wire would have acted as the anode for this event and the HVDC -450KV pole conductor would be the cathode.

The weather on 2/25/18 at the time of the event was heavy dense rain and fog with a violent lightning storm in the area. A lightning induced surge occurred on the K60 shield wire due to a strike to the Sheffield Substation grounding system with a resulting flashover to the -450KV HVDC pole conductor. This very long arc could only be sustained as long as there was an ample supply of positive ions from the anode and electrons from the cathode.

The HVDC – K60 shield wire fault apparently self-extinguished and no HVDC control action took place. The K60 shield wire zinc coating vaporizes at a relatively low temperature (907º C) and would quickly vaporize to the steel layer at which point the supply of ions would be greatly restricted. The restricted supply of ions would increase the arc resistance until the arc extinguished. The arc could only be sustained only as long as there was a supply of vaporized metal at the anode end. The shield wire zinc (419.5ºC melt, 907ºC boil) would have melted & vaporized at the arc point at a much lower temperature than would melt the steel (1450ºC melt, 2792ºC boil). The marks that were left on the shield wire are the 907ºC anode point and the resulting melting of the surrounding zinc that occurs at 419.5ºC. The arc established and decayed linearly as the anode zinc was vaporized until there was not enough positive ions left to support the arc.

Once the HVDC -450KV pole to ground (K60 shield wire) fault occurred, the HVDC fault current flowed via the lowest resistance paths to return to the Radisson Converter Station Rectifier via the Radisson Earth Electrode. The HVDC fault current flowed to ground via all available paths from the shield wire and collected itself at the Sheffield substation. Sheffield likely has a great ground connection with a very low ground mat resistance compared to all of the other ground connections in Northern Vermont. The very low ground resistance at Sheffield could also have been due to the lightning strike at Sheffield which had just ionized a path to true-earth. The HVDC fault current flowed on the lowest resistance path from the fault location of the grounded K60 shield wire to the Radisson Converter Station Rectifier. This path included the Northern Vermont 115KV and 34.5KV transmission system. DFR records from six Velco substations are included in the appendix of this report.

A picture of the suspected "cathode Spot" on the HVDC pole conductor is shown below.



Arc Mark HVDC Pole Conductor Photo 0355

The dates of the prior suspected HVDC K60 shield wire faults is unknown. A review of area DFR records has identified two prior events (7/23/2014 & 5/30/2015) where DC current may have flowed in Northern Vermont AC power system. These events require further analysis.

f. Sheffield DFR Analysis

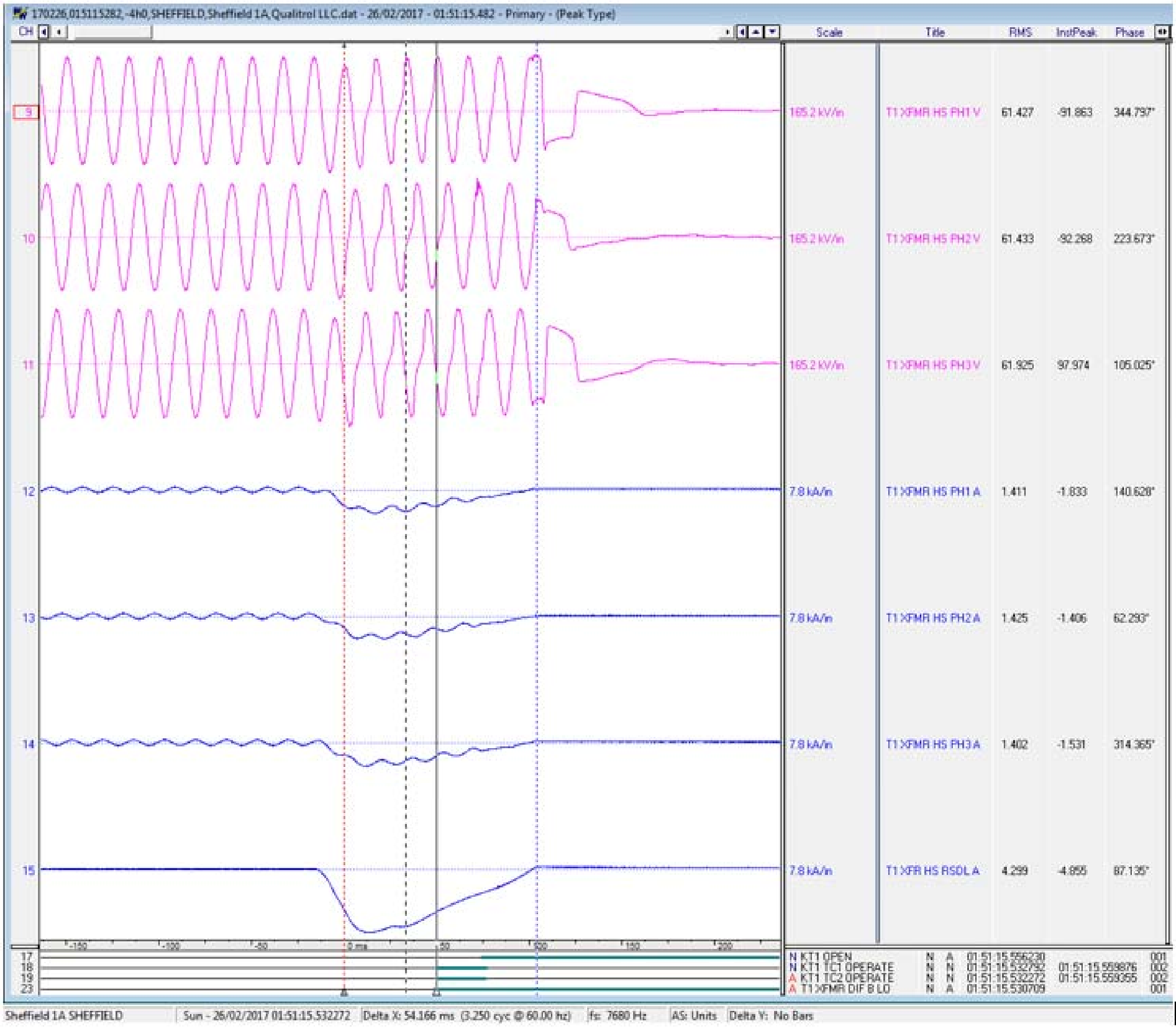
The below DFR record provides the Sheffield T1 115KV currents and voltages. The RMS quantities shown are KV and KA. The time/date noted is UTC time (EST = -5hr). The DC ground currents peaked at approximately 3I0 = 5200A DC, Iphase = 1730A DC. The currents at the time of trip coil operation were 3I0 = 4300A, I_{Phase} = 1430A DC. The DC current extinguished 3.25 cycles after the KT1 and K47 trip coil operation.

The Sheffield 115KV substation is a ring bus arrangement. The Sheffield One line is below.

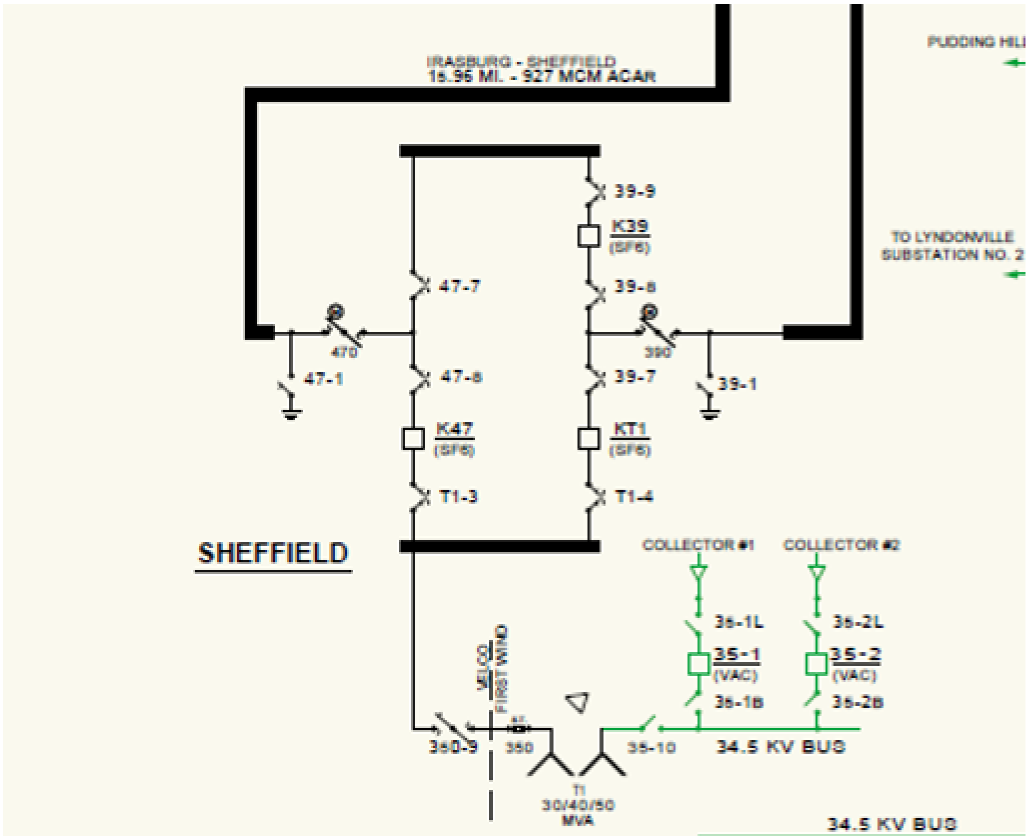
The Sheffield K47 and KT1 115KV circuit breakers tripped during the event and had sustained DC current flow while the contacts were open. The breakers were inspected and no unusual contact wear was noted.

The Sheffield 115KV bus voltages sagged to 0.92 pu and exhibited extreme distortion during the event.

Rated AC current for the 30MVA T1 transformer is 151A at 115KV. 1730A DC per phase flowed through the grounded 115KV windings of this transformer.
The Sheffield T1 transformer testing has revealed no abnormal conditions from this event.



Sheffield DFR Record



Sheffield One Line

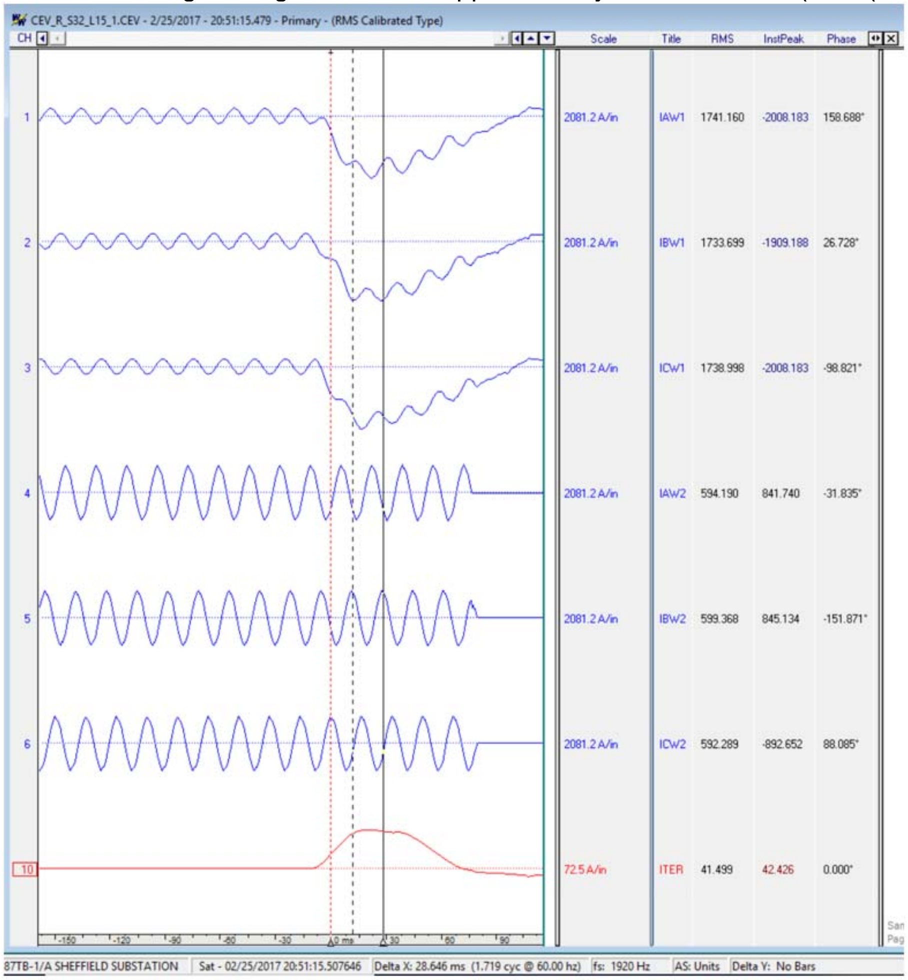
g. Sheffield Transformer Protection Operation Analysis

The Sheffield T1 is a 30/40/50 MVA, 115KV/34.5KV/13.8KV wye-grounded/wye-grounded transformer with a delta tertiary. It is protected with a multifunction numerical transformer protection system (87T1P) as the primary protection and a transformer differential relay (87T1S) as the secondary protection.
Additional backup 115KV phase and ground overcurrent protection is provided by the a separate 67-67N-1/BU multifunction numerical relay.

The 87T1S transformer differential relay differential relay operated incorrectly for the DC current flow. The relay phase compensation jumpers “IN1 J1” and “IN2 J2” are set to “DELTA1” which should have removed the zero-sequence quantities from the phase currents. The DC ground current was a pure zero-sequence quantity. This relay is not designed for operation with DC current flow. The security of this relay could be improved for this very unusual current flow condition by connecting the CT’s in delta to externally filter the zero-sequence current. This is not recommended since the relay has been secure for all other external fault conditions.

The 87T1P numerical differential protection correctly restrained for the DC current flow. The winding 1 currents are the summed 115KV currents from K47 & KT1. The winding 2 currents are 34.5KV currents from wind farm 34.5KV collector breakers 35-1 & 35-2. The transformer differential winding compensation setting W1CTC setting = 12. This setting filters the zero-sequence component from the winding 1 phase currents. The DC ground current was a pure zero-sequence quantity and the relay correctly restrained when these currents were filtered from the differential calculation.

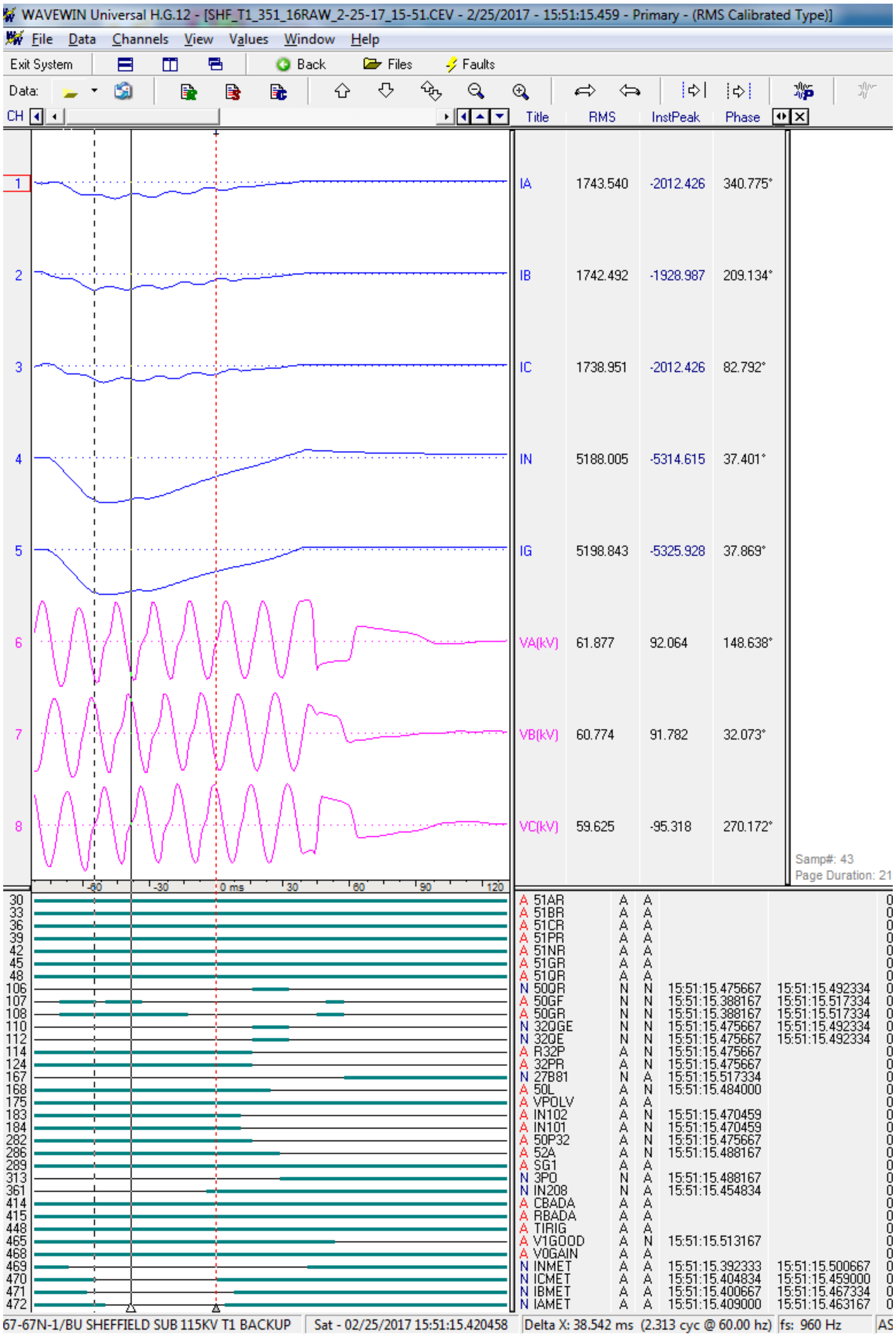
Relay event report data is shown below. The ITER current value is the 13.8KV transformer tertiary displayed in secondary amps, 41.5A secondary, 6640A primary. The transformer was operating at the 117.88KV tap. The transformer magnetizing current was approximately 1740A – 6640 *(13.8/(117.88/√3) = 394A per phase.



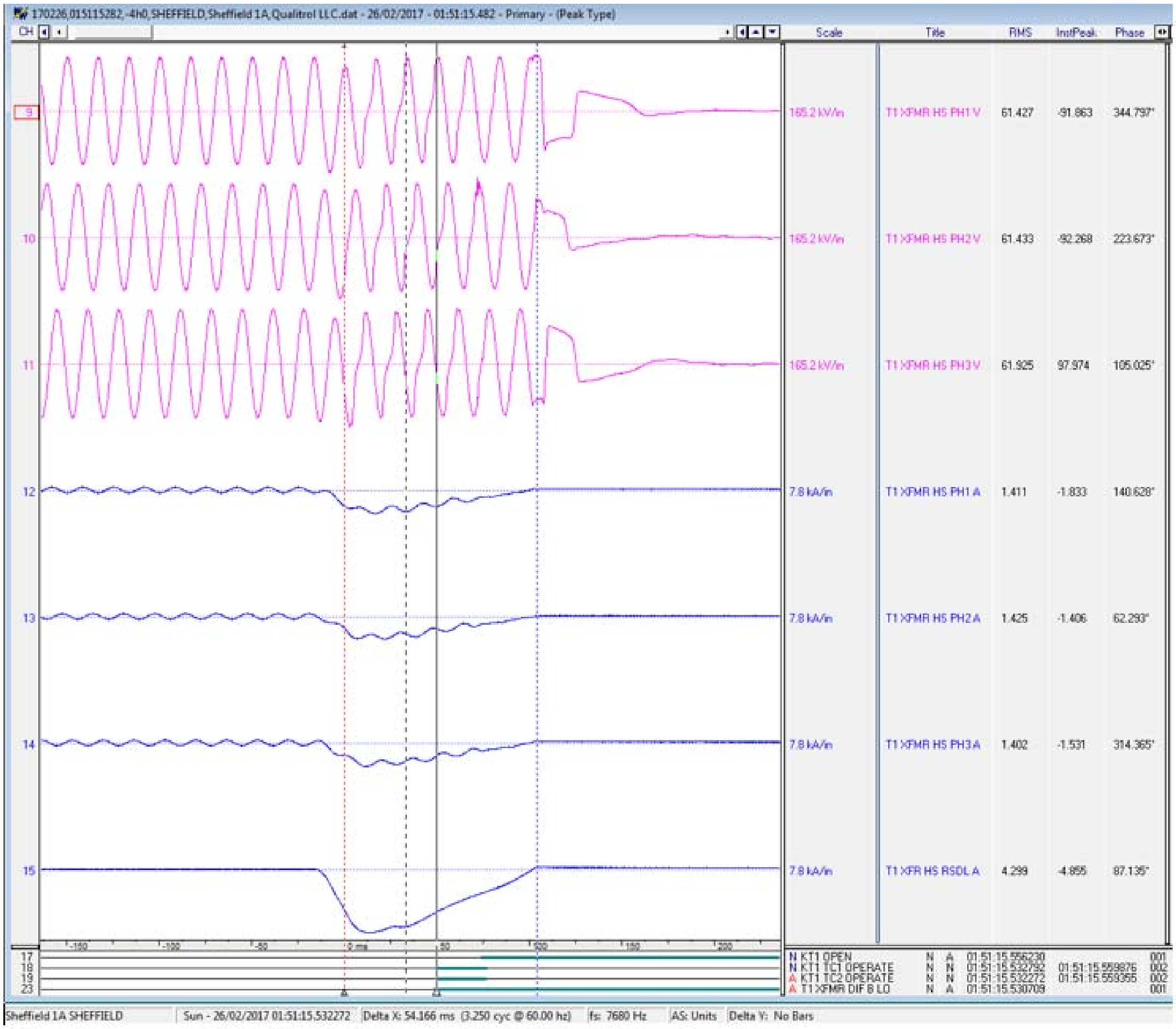
Sheffield T1 SEL387 Event Report

The Sheffield wind farm was generating approximately 35 MVA during the event and the wind farm output (winding 2 currents) was not affected by the presence of DC currents in the T1 transformer windings.

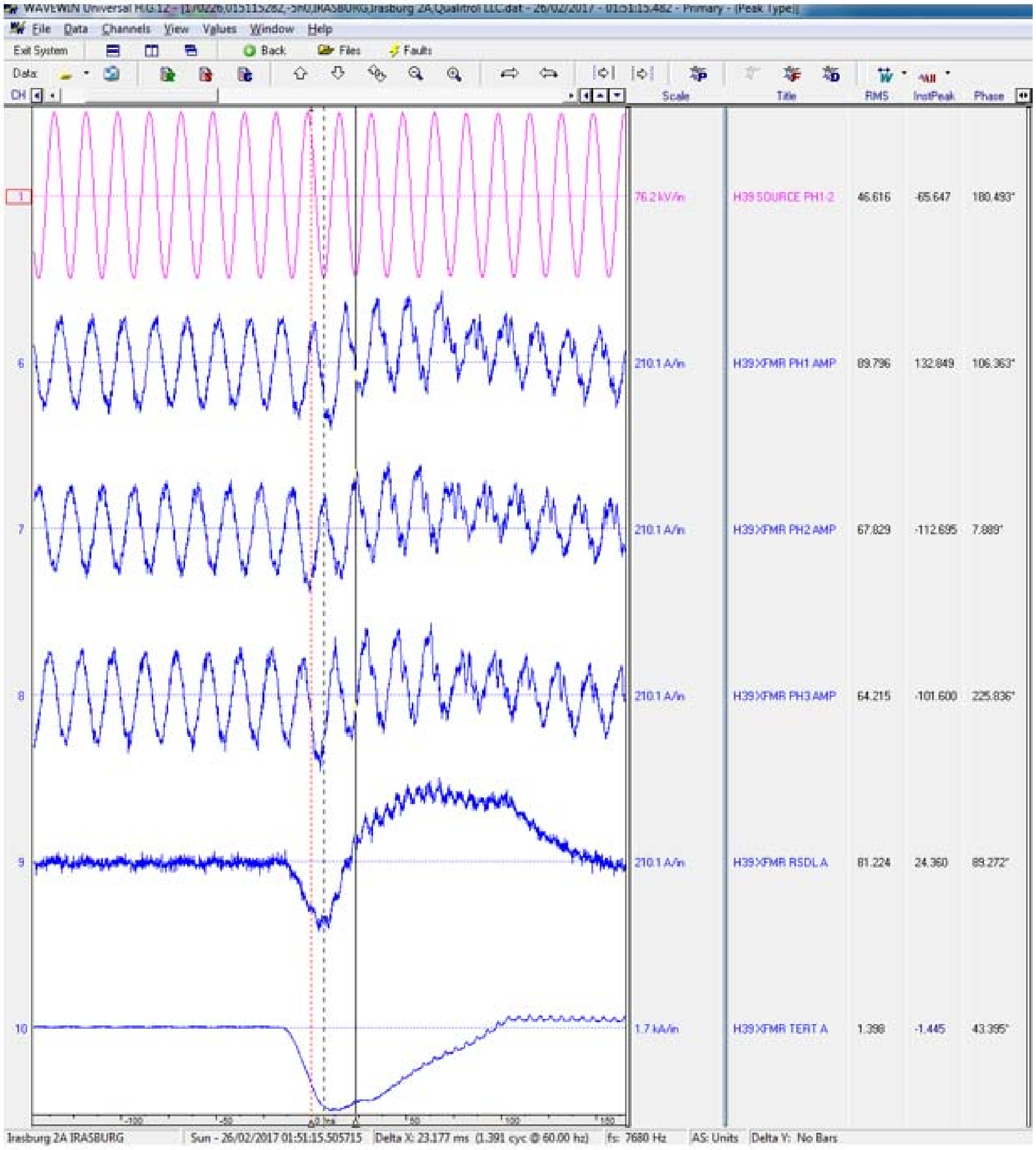
The 67-67N-1/BU relay did not operate for the DC current flow. This relay was set with negative sequence directional elements which would not operate for this zero-sequence overcurrent condition. This relay is not designed for operation with DC current flow.



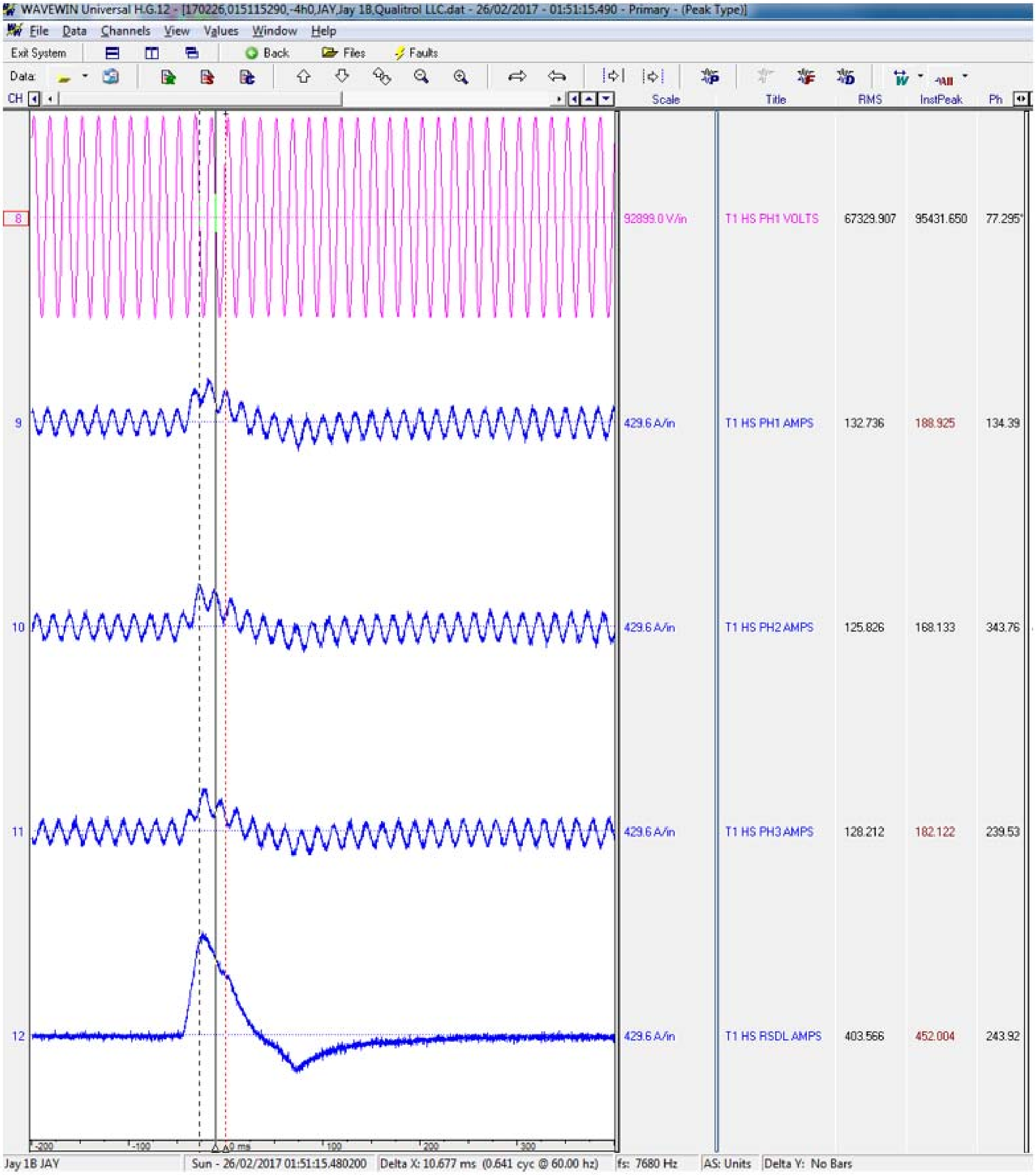
3. DFR Records of DC Ground Current Flow



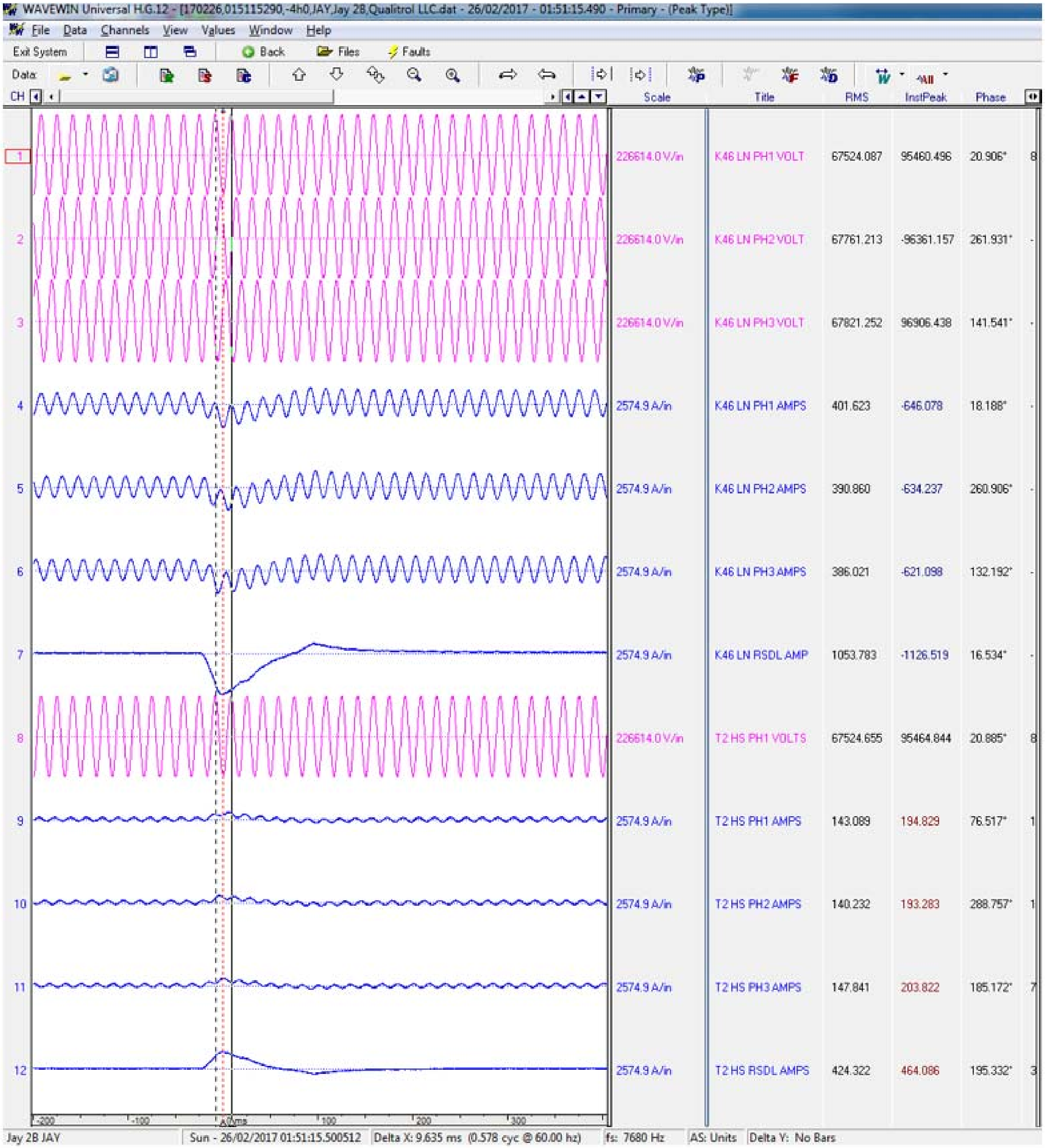
Sheffield T1 115KV/34.5KV/13.8KV three winding transformer



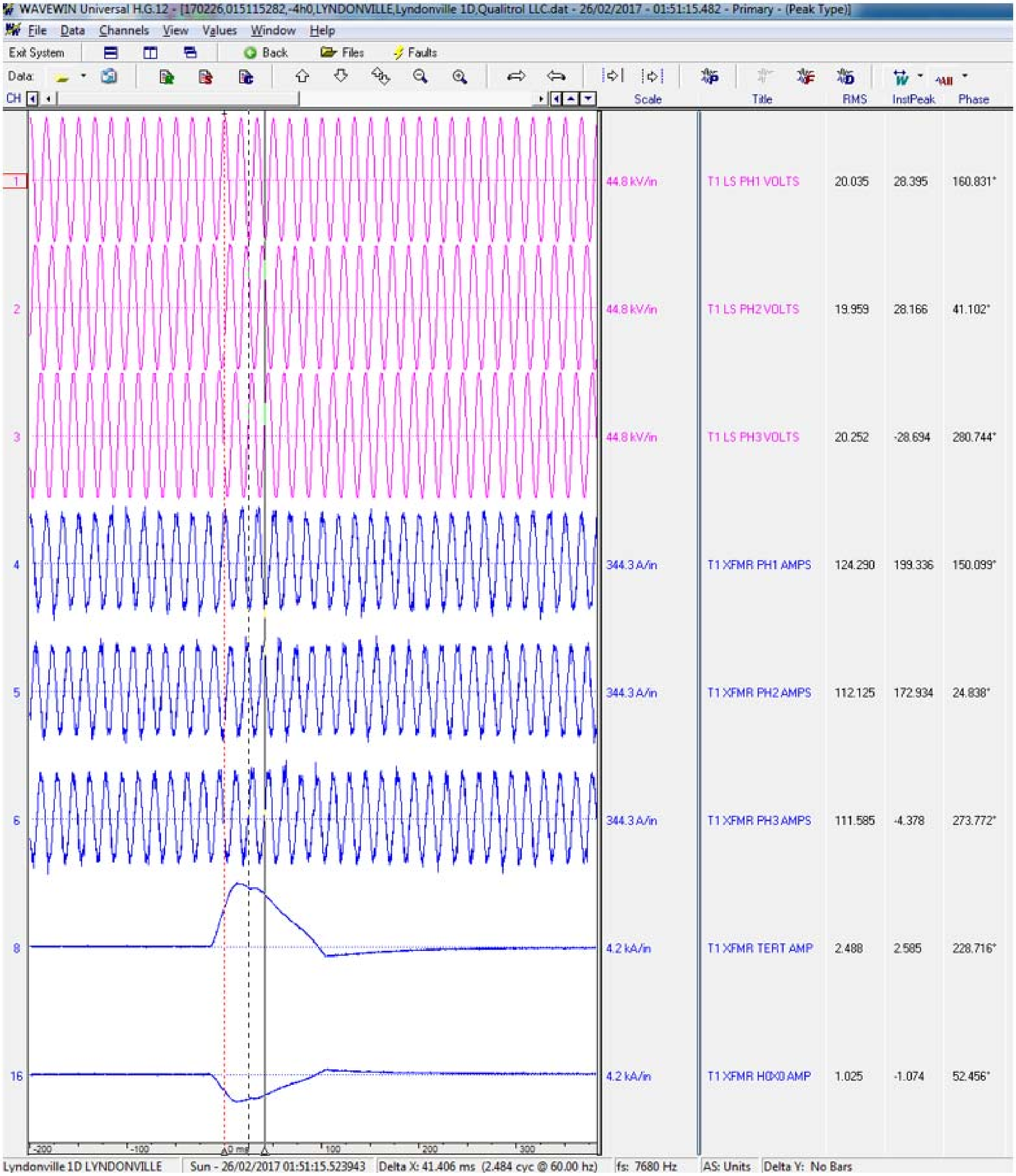
Irasburg 115KV/46KV Autotransformer



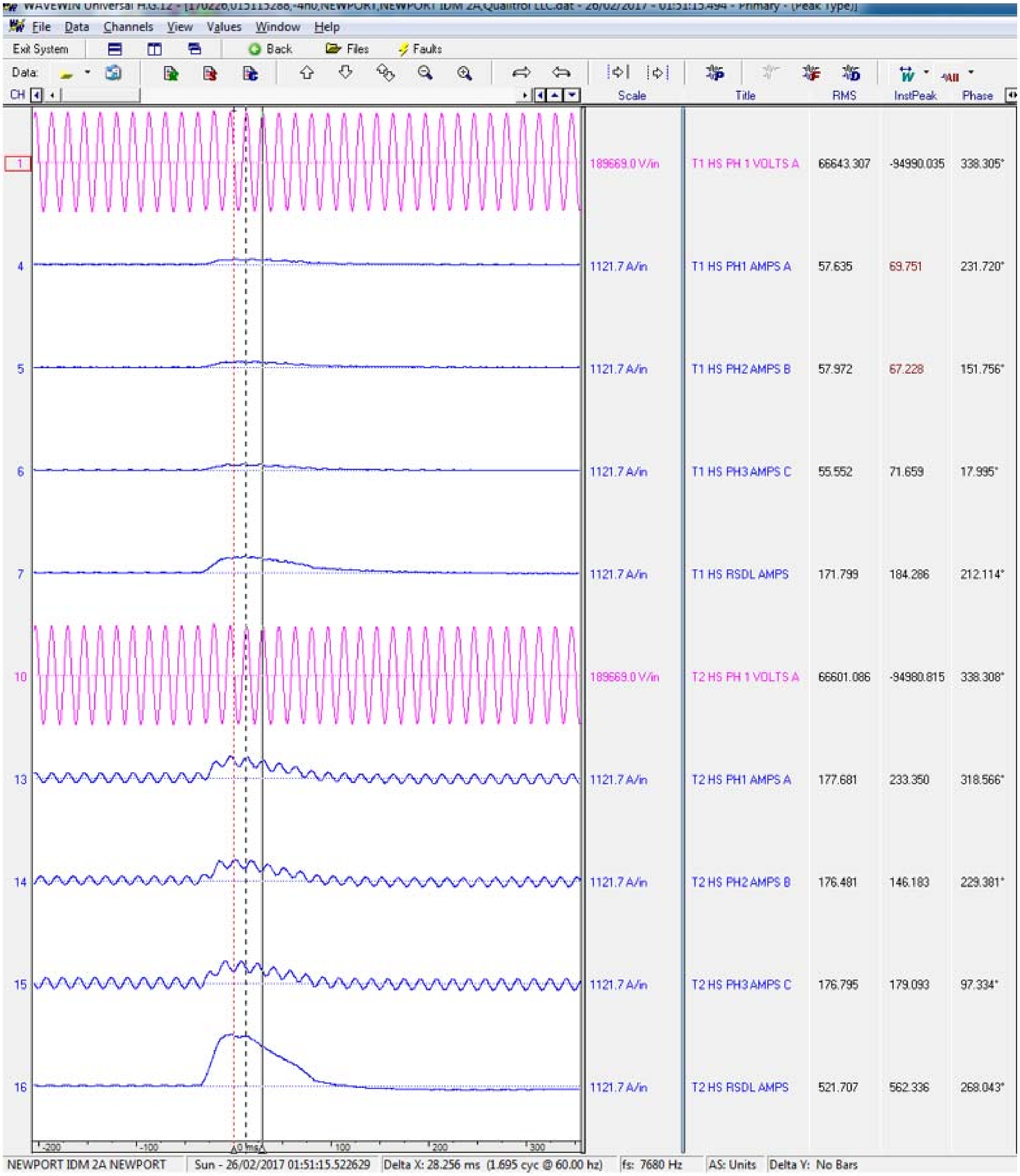
Jay 115KV/46KV T1 Autotransformer



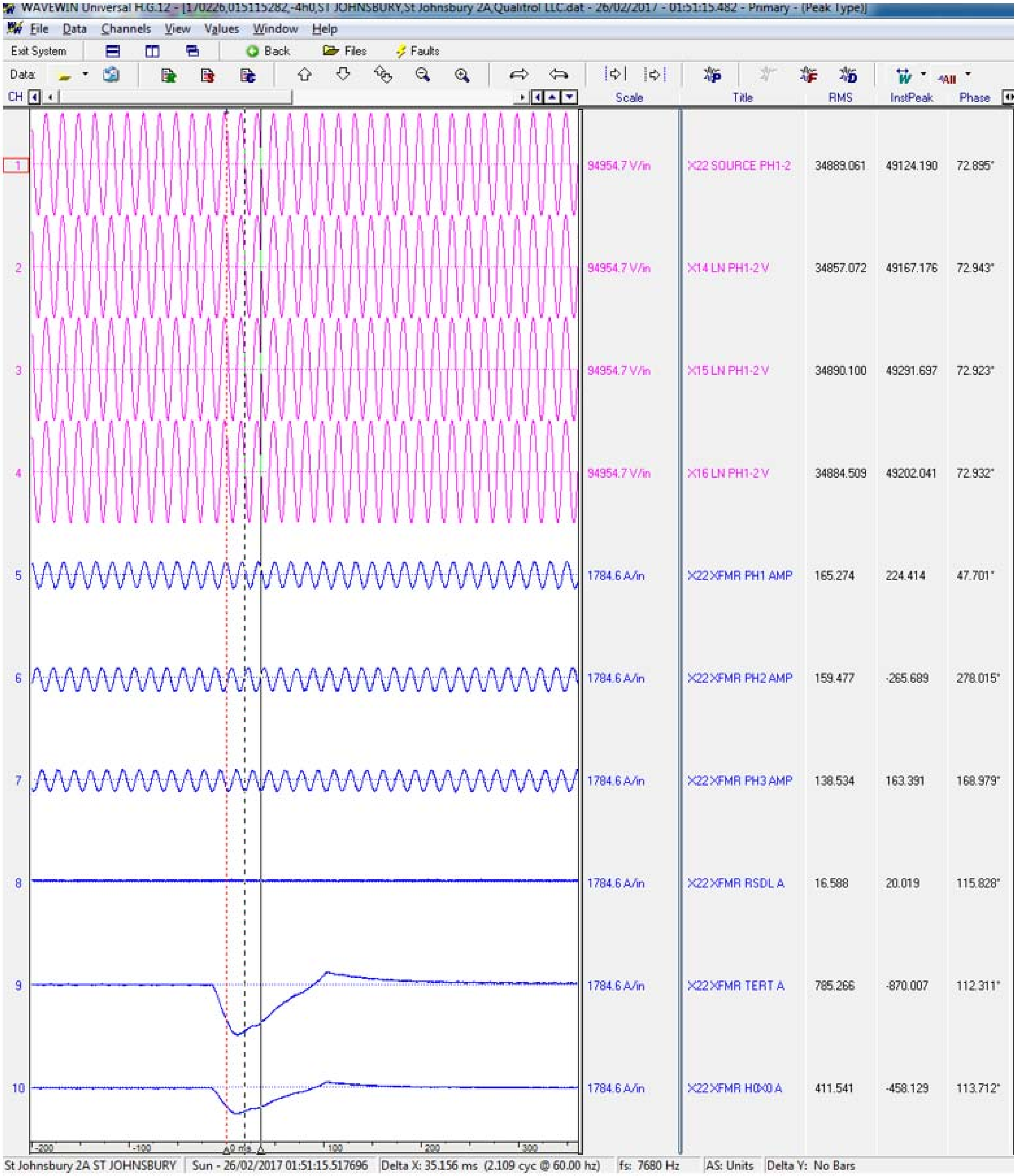
Jay 115KV/46KV T2 Autotransformer



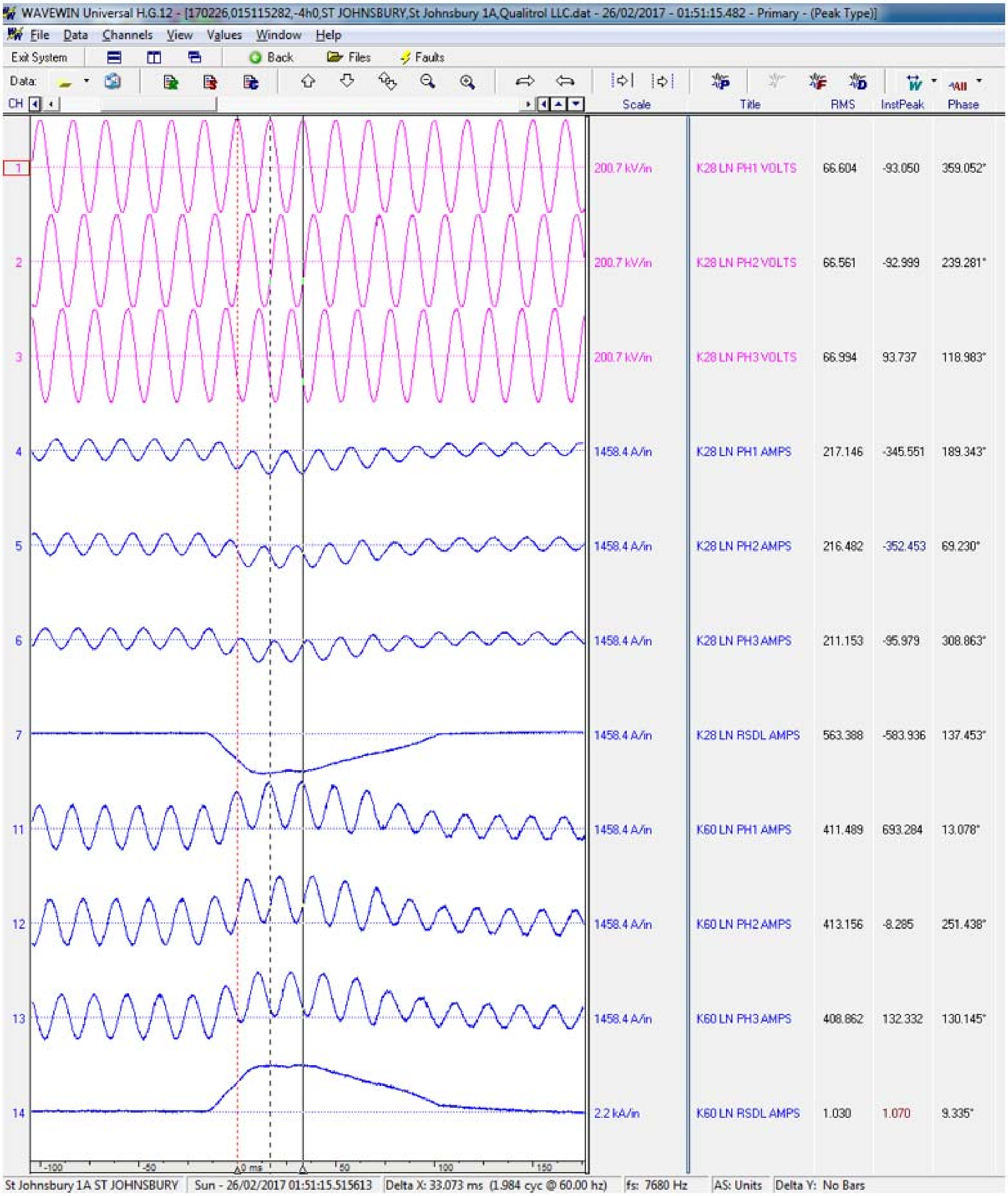
Lyndonville 115KV/34.5KV T1 Autotransformer



Newport 115KV/46KV T1 Autotransformer & Newport 115KV/46KV T2 Autotransformer



St. Johnsbury 115KV/34.5KV Autotransformer



St. Johnsbury 115KV/34.5KV Autotransformer

Biographies:

Frank P. Stacom, P.E. was born in the Bronx, NY on May 2, 1957. His entire 40+ year career has been electric utility Protection & Control Engineering which included fault and disturbance analysis. He received his BEE from Manhattan College in 1979 and started his engineering career with the Long Island Lighting Company (LILCO). He left LILCO in 1982 for the New York Power Authority (NYPA). While at NYPA he received his MEE from Manhattan College in 1987 and completed the GE PSEC course in 1988. He left NYPA in 1998 to join CVPS where he was the Manager of Relay Protection and Principal Protection Engineer. In 2007 he left CVPS to start his own consulting engineering business. His clients include Velco, Eversource, GMP, Eaton, ECNE, Entergy, CVPS, CUC and ABB. Frank is a registered Professional Engineer in VT & NY. He is also an Inventor, recently receiving his first patent.

Ed McGann, PE. Manager of Engineering at Vermont Electric Power Co. (VELCO). VELCO owns and operates the electric transmission grid in the state of Vermont which consists of 738 miles of transmission lines and 55 substations, switching stations and terminal facilities. Mr. McGann has 16 years of experience in bulk electric transmission engineering with an emphasis in protection and control design and system operations support.