Analysis of Cascading Operations for Adjacent Line Faults At National Grid

By: Yujie Irene Lu, Song Ji & Scott J. Slaski (National Grid)

Introduction

Circuit design, equipment age, rating limitations and Mother Nature can all factor into a single cascading power system disturbance and when combined can present great challenges in post event analysis. One such event occurred on the National Grid transmission system in the New England region during June of 2013 resulting in the unexpected outage of a 345/115kV autotransformer, one 345kV circuit breaker and seven 115kV circuit breakers at a single substation interrupting services to customers and impacting system reliability; a major concern for the Regional Transmission Operator ISO New England and National Grid. To determine the cause of this complex event, National Grid put into play several different investigative tools. Strategic placement and use of digital fault recorders, fault simulation software, and empirical field test data were all necessary to analyze and explain this cascading disturbance.

This paper retraces the aforementioned cascading system disturbance and post event analysis performed by National Grid to share technical insights derived from the study and to convey the wide variety of tools needed to analyze such a complex operation. The system configuration will be illustrated, a timeline of faults and operations will be detailed and questions presented immediately following the event will be posed and answered with supporting technical data. This paper will close by recapping the operation and the analysis tools needed to reach closure and key lessons learned from the event.

System Overview

Substation Carp consists of one 345/115kV step-down autotransformer, one 345kV circuit breaker and eight 115kV circuit breakers. The 115 portion is arranged in three bays with a breaker and a half scheme. It is supplied by one 3-terminal 345kV line from substations Mill and Lud and three 2-terminal 115kV lines from substations Mill, Palm and Millen. . The remaining two 115kV lines leaving Carp supply load to the local distribution substation Snow. The autotransformer connects to the 115kV section in one of the breaker and a half bays. Many years ago the 115kV bus was configured different than it was at the time of this event, indirectly contributing to this operation as will later be pointed out. The substation and faulted line configuration are shown in Figure 1a and Figure 1b.

Redundant systems of solid state and microprocessor based relays protect the circuit breakers, lines, buses and transformers at Carp. A stand alone digital fault recorder (DFR) monitors analog voltage and current waveforms on the autotransformer and all lines and buses in addition to tracking the status of all key protection and control devices in the substation such as breaker open-closed indication, relay trips, breaker failure initiates and lockout operations and so forth. National Grid performs a monthly maintenance test on the DFR to ensure functionality.

Incident Summary

In the early afternoon of Friday, the 28th of June, 2013 areas of central New England were experiencing thunderstorms. National Grid's substation Carp is situated on the 345 and 115kV transmission system in this region of New England and fell victim to a cascading system disturbance initiated by the storm. Prior to the event all primary devices at the station were in the normally closed position and energized carrying system load with all associated protection systems in service. No work crews were in the station at the time.

On June 28th, 2013, the National Grid Control Center reported that:

At 14:35:09.173, a lightning stroke caused a B and C phase to ground fault on the 115kV line 73 near substation Carp. The line protection operated and tripped the breakers 73 and 73-74 correctly, which isolated the fault. Per fault records collected from the DFR at substation Carp, the fault was 1.72 miles away the station and the line 73 and breakers 73 and 73-74 were tripped in 3.5 cycles. Simultaneously the sudden pressure protection of 345/115/13.2kV #1autotransformer also operated tripping and locking out the transformer high side 345kV breaker 30 and low side 115kV breakers 1T and 23-1T (Figure 1a).

At 14:35:09.938, approximately 0.8 second after the first fault, the line 73 was hit again by another lightning stroke at almost the same location causing a B phase to ground fault. Although breakers 73 and 73-74 remained in the open position, the line 73 protective relay operated again on the second fault and three surrounding breakers, 23, 21 and 75, were tripped and locked out by the 73 and 74 breaker failure schemes. In addition, a direct transfer trip (DTT) signal was sent down the line 23 by the 73 breaker failure scheme tripping the customer owned Millen station offline. The only breaker that did not trip was the 74 though loss of the autotransformer and other 115kV lines left the line 74 dead. Approximately 12,700 customers at the other end of the line 73 and 23 without power (Figure 1b).

Three substations were lost in roughly 1 second as a result of the lightning hits and subsequent sudden pressure trip and breaker failure operations.

Initial information on how this event occurred came in the form of relay targets reported from the Carp substation by first responders. The relay targets were reported as follows:

Carp: Line 73 Directional Distance Zone 1 B and C Phases (21/21N/67N-73, DDZ1)

Breakers 73 and 73-74 Breaker Failure Common Timer (62-3)
Breakers 74 and 73-74 Breaker Failure Common Timer (62-2)
Breaker 73 Breaker Failure Lockout (86-73)
Breaker 74 Breaker Failure Lockout (86-74)

#1 Transformer Sudden Pressure (63PF-T1)

Regarding the lightning strokes all 115kV lines involved are provided with overhead shield wires. No surge arresters are installed on the line side of the circuit breakers at Carp substation. Studies suggest the first line fault was caused by insulator string back-flash following the lightning stroke on the shield wire while the second fault was a direct stroke on the line conductor. A simplified EMTP simulation for the second fault suggested the electrical stress on the breaker 73 exceeded the breaker BIL, breaking down the insulation across the B Phase open main contact of the breaker 73. See detailed analysis in Section of **Analysis of the Conduction of Open Breaker 73 during the Second Lightning Stroke** in this paper.

Two thunderstorms were confirmed to have passed over the 115kV line 73 in less than 0.8 seconds, causing the two separate line-to-ground faults. The magnitude of the lightning discharges and rough locations were recorded by the National Lightning Detection Network (NLSN) at the National Grid Control Center and are shown in the Figure 7.

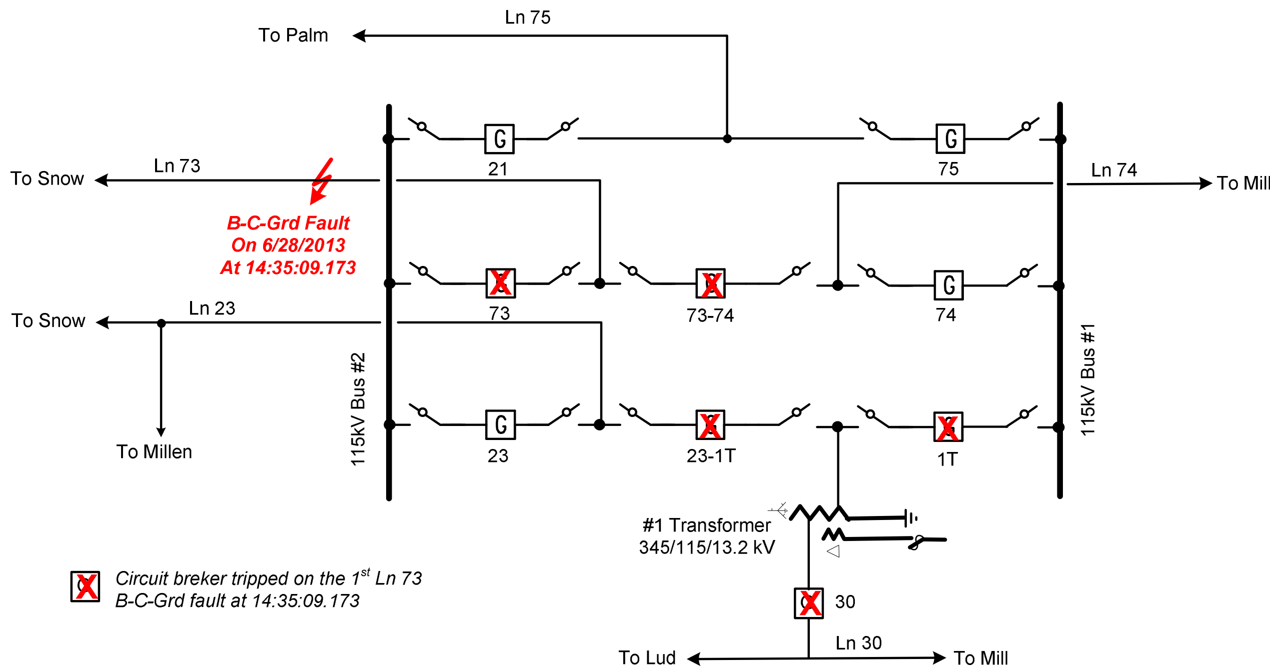

Figure 1a: Substation Carp System One Line Diagram & Breaker Status after the 1st Fault

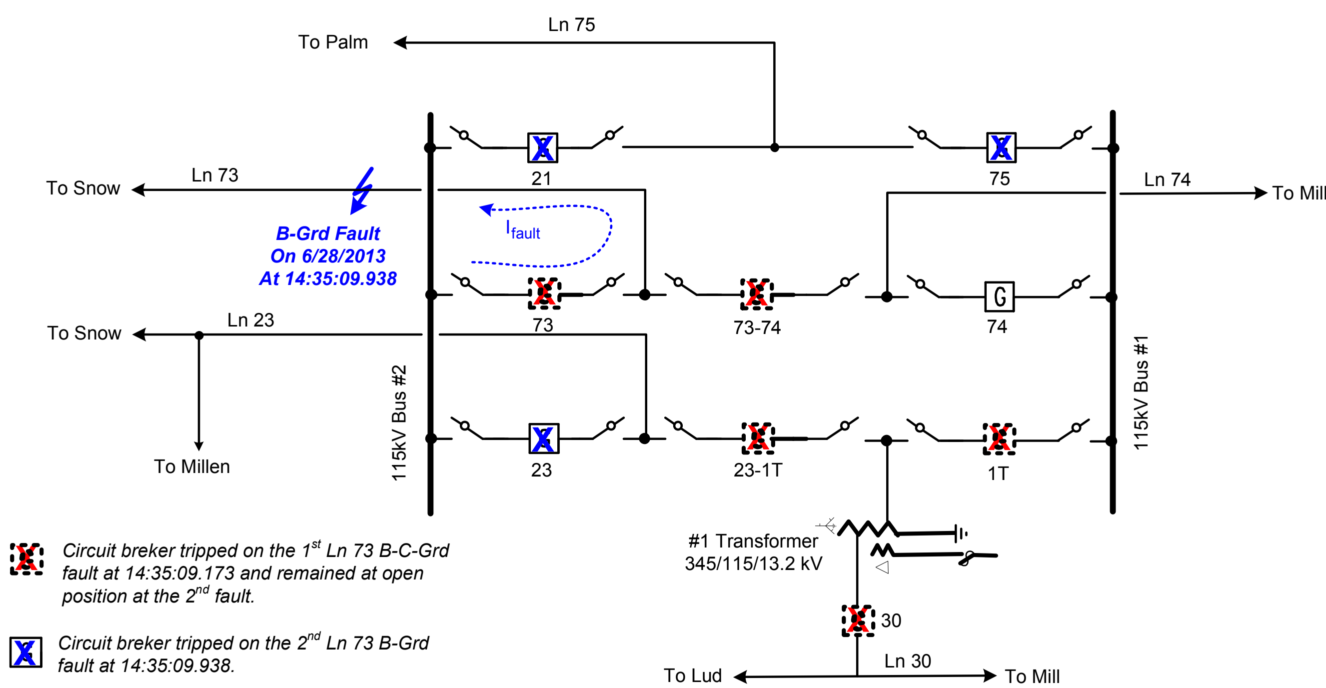

Figure 1b: Substation Carp System One Line Diagram & Breaker Status after the 2nd Fault

Investigation and Analysis

First, the disturbance investigation began with collection and review of relay targets, Sequence of Events (SOE) data and fault records captured by the digital fault recorder (DFR) at the substation Carp. Based on the reported relay targets and the captured fault records, it was confirmed that:

- The phase directional distance zone 1 function (DD Z1) out of the faulted line 73 relaying sensed the original B to C phase to ground fault and correctly tripped the 115kV bus breaker 73 and tie breaker 73-74 in 3.5 cycles.

- Simultaneously, 345/115/13.2kV #1 transformer sudden pressure relay also sensed the original line 73 fault and tripped out the transformer.

- Although breakers 73 and 73-74 remained in the open position, the same instantaneous function of the line 73 relay operated again on the second fault and three surrounding breakers, 23, 21 and 75, were tripped and locked out in 12 cycles by the 73 and 74 breaker failure relays.

Based on the findings described above, the investigation focus moved to identify why the transformer sudden pressure relay improperly responded to the external line fault and why the line 73 relay operated again on the second fault and initiated the two breaker failure schemes for the surrounding breakers.

1. Why did the transformer sudden pressure relay operate on the line 73 fault?

At National Grid the sudden pressure relay is used to detect and isolate faults occurring inside a transformer. The sudden pressure relay is mounted on the side of the transformer to detect pressure waves within the unit. The mechanical sensor of the relay consists of a bellows and a pressure equalizer which are not sensitive to slow changes of pressure such as the changes caused by loading however a pressure wave created by a nearby fault can be detected by this relay. Per statistical data on misoperations involving this type relay at National Grid and other utilities in the US, sometimes these relays are found to be too sensitive and may respond to transformer winding movement caused by severe external fault currents [1] & [2].

Multiple factors were taken into consideration to determine if the #1 autotransformer did experience a rapid pressure rise:

- The transformer itself is over 40 years old and approaching the end of its serviceable life. Its construction is of the tank type with a gas cushion at the top of the tank.
- The sudden pressure relay had been replaced in years past due to previous suspected misoperation and the replacement relay currently in service tested within an acceptable sensitivity range.
- The external fault on the line 73 was relatively close to the Carp station thus fault current magnitude experienced by the transformer during the fault was significant.
- Fault recorder data did not show evidence of an internal transformer fault.

A transformer Sweep Frequency Response Analysis (SFRA) test was performed by Doble Engineering on July 28th, 2013 on the Carp autotransformer. Doble and National Grid concluded that there is operational and testing evidence that the fault events have caused winding movement to the Carp #1 autotransformer since the time it was manufactured and sometime during the period between 2006 and 2013. The Doble SFRA testing indicates winding movement in the 13.2kV tertiary Y1-Y2 leg. The leakage Reactance testing performed on the same day and hinted the same winding movement happened that the SFRA highlighted [3]. The highlighted SFRA test result from Doble is listed in Figure 3.

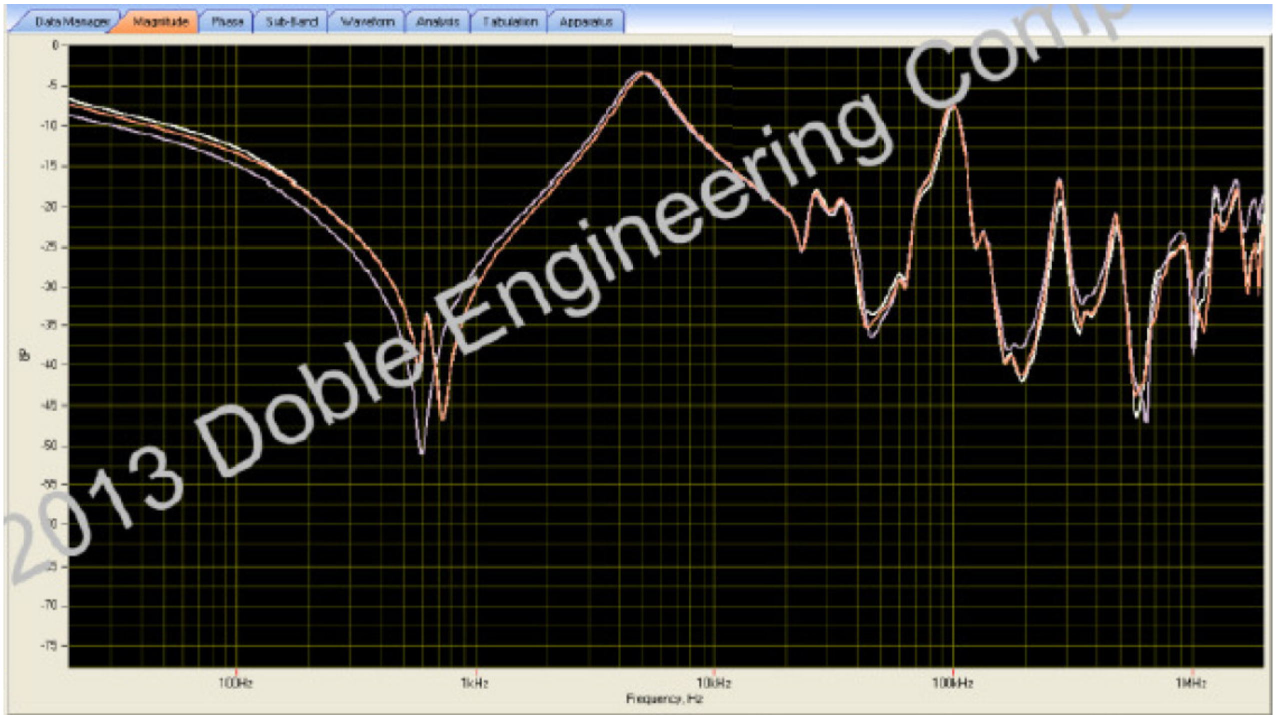

Figure 2: typical expectation of transformer SFRA results

Figure 3: Doble SFRA Test Result on #1 Transformer at Carp on 7/28/2013

Figure 3 is a snapshot of the 2013 SFRA open circuit tertiary measurements for transformer T1. This snapshot reveals that there is a significant mismatch of one of the traces (light blue -Y2-Y1) when compared to typical expectation for alignment demonstrated in picture above. The deviation starts at 60 kHz and continues on up which is associated with bulk components changing location and winding geometry changing [3].

2. Why did the line 73 relay sense the fault current and operated again on the second fault when the line breakers 73 and 73-74 remained in the open position?

By analyzing the Carp DFR records as shown in Figure 4 on the following page, it was determined that:

- During the original line 73 fault, the line protective relay operated and tripped the breakers 73 and 73-74 correctly isolating the fault in 3.5 cycles. Both breakers remained in the open position following this trip.

- On the second lightning hit all four 115kV lines (73, 74, 75 and 23) at Carp saw B phase to ground fault current. Fault current of line 73 was out of the Carp 115kV bus toward the fault. Fault current through lines 23, 74 and 75 were only apart 40 degrees from each other but apart almost 180 degrees from the current through the line 73, i.e. the current of 23, 74 and 75 was into the bus. This finding suggested that the second fault was on the line 73 and the line 73 relay operated again. In addition, magnitude summation of the fault current of the 23, 74 and 75 is equal to the current on the 73 (Figure 5).

The breakers 73 and 73-74 for line 73 were in the open position at the moment of the second line fault. How could the line 73 see the through fault current if both line breakers were open? Based on the SOE data and relay targets, it is highly suspected that the main contact insulation of the breaker 73 was experienced a dielectric breakdown by the high energy of the lightning stroke, therefore, the current did in fact feed from bus to line although physically the breaker was open at the time.

The breaker 73 was tested in the field after this cascading event, but no problem could be identified. To further investigate on this breaker issue, a simplified EMTP simulation was performed. Results of the EMTP simulation confirm that surges caused by the second lightning stroke were sufficient to cause insulation failure on the 73 breaker. For detailed analysis and simulation results see the section labeled **Analysis of the Conduction of Open Breaker 73 during the Second Lightning Stroke** beginning on page 13 of this paper.

3. What caused both the 73 and 74 breaker failure relays to operate on the second line 73 fault and tripped out the surrounding breakers?

A station Carp DC Schematic review revealed the presence of "shared" electromechanical timer relays in the 115kV breaker failure schemes. These timers are initiated for any line or bus relay operations, if the timer is asserted for longer than the expected fault clearing interval the timer will cue multiple breaker fault detector over current relays (hence the term "shared") to see if fault current is still present through the breaker CTs. If one of the breakers is showing amps above the fault detector current threshold the fault detector relay will trip a corresponding breaker failure lockout without any further time delay.

Specifically for the circuit in question it was noticed that 73 and 73-74 breaker failure schemes share a common timer (62-3) while the 74 and 73-74 breaker failure schemes share another common timer (62-2). The 115kV breaker failure scheme for a line 73 fault is illustrated in the flow chart of Figure 6 on page 11 of this report.

Approximately 0.8 second after the original fault, the line 73 relay operated again on the second fault. At the same time, the 73 breaker failure fault detector (BF-FD) picked up since the fault current sensed was higher than its pickup value. Referring to Figure 6 and DFR records, as soon as the second fault occurred, the 73 and 73-74 breaker failure initiate (BFI) auxiliary relays, BFI-73 and BFI-73-74, were initiated following the line 73 protection trip command, which started the 73 and 73-74 breaker failure common timer, 62-3, and the 73-74 and 74 breaker failure common timer, 62-2. Due to the main contact insulation of the breaker 73 breaking down by the high energy of the lightning stroke as discussed previously, the fault current remained present on the line 73 although physically the breaker was already open prior to the second fault.

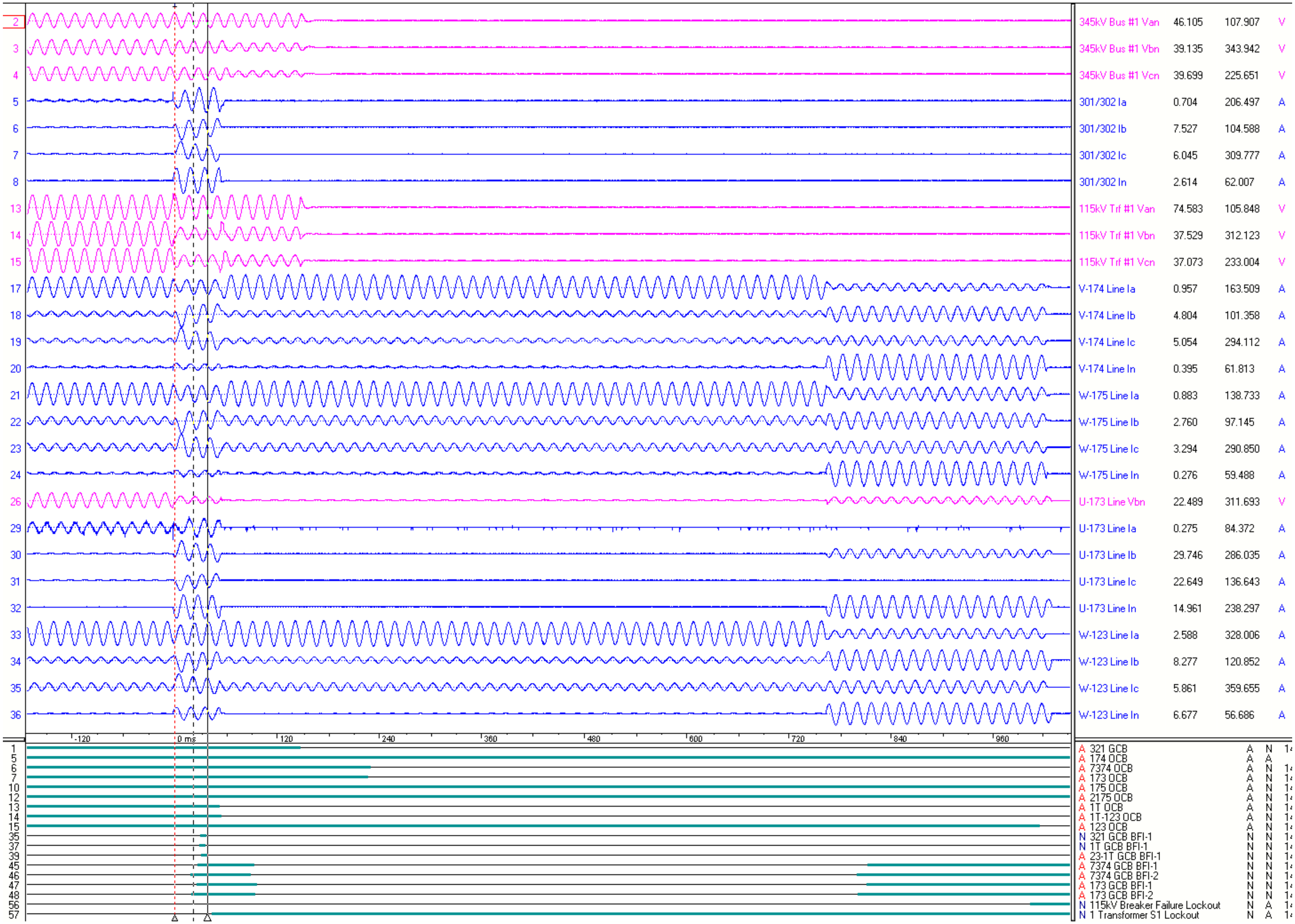

Figure 4. Carp DFR Records on Line 73 Faults on 6/28/2013, at 14:35:09.173 and 14:35:09.938

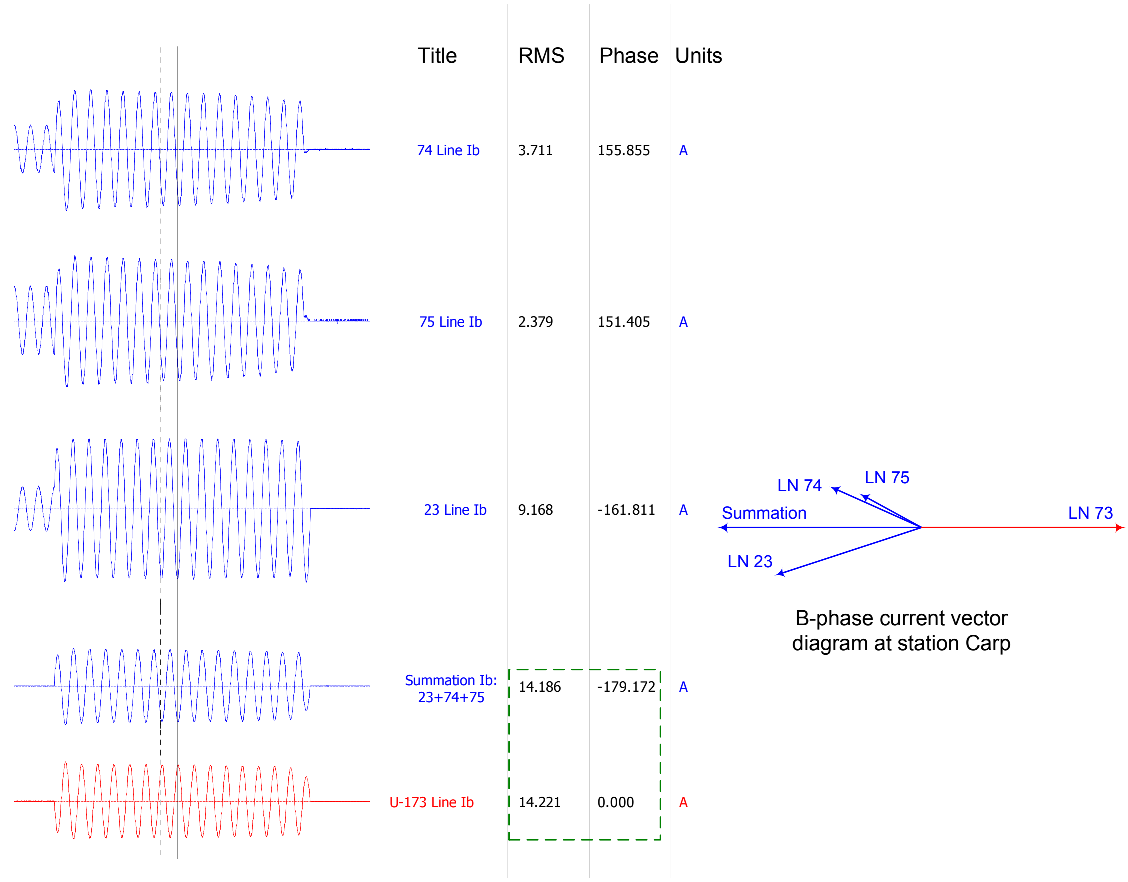

Figure 5: The B-phase current flow information during the second lightning stroke at Carp

With no way to clear the second line 73 fault because of the internal arc at the breaker 73, the shared 62-2 relay timed out in 12 cycles (the BF timer setting) and cued the 73 BF-FD relay to trip the 73 breaker failure lockout. Per the tripping schedule breakers 21 and 23 cleared and a DTT signal was sent to station Millen. Clearance times for the breaker failure condition helped explain why the second fault lasted for 15 cycles.

Referring to the BF scheme logic illustrated below in Figure 6 and the collected target information on the 73-74 and 74 breaker failure common timer, 62-2, and the 74 breaker failure lockout relay, 86-74, it can be seen that the breaker failure scheme responded to the second fault as well because the 74 BF FD remained picked up until the second line 73 fault was isolated by the 73 breaker failure relay, which indicated why the breaker 75 was tripped at the same time as the breakers 23 and 21 opened in 15 cycles.

Through review of the 73, 73-74 and 74 breaker failure schematic drawings and relay targets captured during the line 73 faults, the reason of the 74 breaker failure operation along with the 73 breaker failure operation was discovered and traced back to incorrect cross-tripping between the 73, 73-74 and 74 breaker failure common timers, 62-3 and 62-2 (Figure 6). The design error was made while re-building part of the 115kV switchyard and modifying the 115kV breaker failure scheme from one breaker failure timer per bus to one timer per breaker in the early 2000.

Corrective actions have been taken based on the above finding of the breaker failure circuit flaw. The investigation team proposed to revise the present 115kV breaker failure design at substation Carp by using one timer per breaker failure scheme rather than shared timers for each 115kV breaker. The re-designed logic for 115kV breaker failure scheme is illustrated in Figure 7 on the following page.

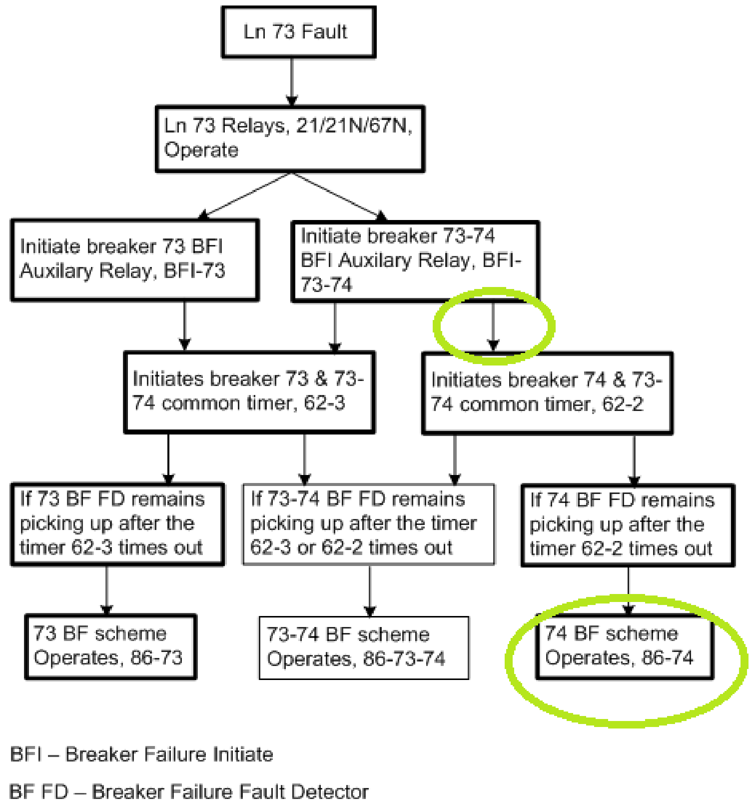

Figure 6: Operation Logic of 73 & 74 Breaker Failure Scheme at Carp during the Second Fault

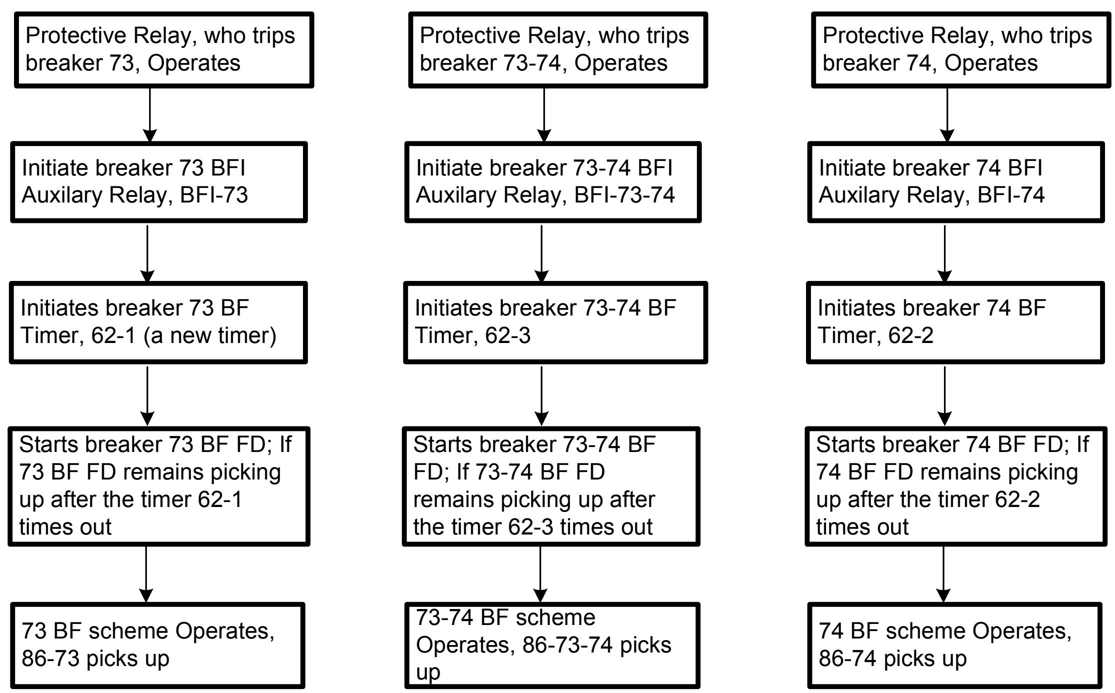

Figure 7: Operation Logic of Proposed 73, 73-74 & 74 Breaker Failure Scheme at Carp

Analysis of the Conduction of Open Breaker 73 during the Second Lightning Stroke:

For the first lightning stroke on 115kV line 73, the line protections at Carp station correctly operated and successfully tripped the breaker 73 to isolate the ground fault. Then, the second lightning stroke hit the same line again in 765ms. The protections for line 73 operated again and tried to trip the already opened breaker 73. The occurrence of persistent fault current and protection trip signal shown in the DFR records did indicate a true breaker failure condition. Since the breaker had been opened, how could the fault current flow through the already opened main contact of breaker 73?

1. Breaker 73 at Substation Carp:

Breaker 73 is 115kV Sulfur hexafluoride (SF6) dead tank 3-phase circuit breaker with BIL of 550kV. “Dead tank” means that the metallic container accommodating the arc interrupting unit and all accessories are maintained at an earth potential. The internal interrupting units are connected to external HV conductors through conventional bushings. The dead tank breaker has some obvious advantages, such as lower center of gravity, good seismic performance, capability to install bushing CTs, ability to operate in extreme cold areas with electric tank heaters.

The interrupting media of the breaker is SF6 gas which is chemically very stable, non-flammable, odorless, colorless, tasteless, and nontoxic in its pure state. For the certain electrode spacing, the dielectric strength of SF6 is approximately three times that of air under one atmosphere pressure. The higher gas pressure will increase dielectric strength because the free path of gas molecules is reduced. Under the pressure of three atmospheres, the dielectric strength of SF6 is equivalent to conventional insulating oil. Furthermore, it has been found that SF6 retains most of its dielectric properties when mixed even with substantial proportions of air or nitrogen [4]. Therefore, the interrupting unit of SF6 breaker can be made in a compact size under proper gas pressure without compromising the arc quenching and insulation capabilities.

Breaker 73 was tested in the field after this event. The SF6 gas pressure was at the normal range and gas purity was more than 99.9%. The operational mechanism was good and the insulation strength across the main contacts was adequate. No issue was found with breaker and further study was required.

2. Lightning strokes and line structures:

Two thunderstorms passed over 115kV line 73 in less than 800 ms and caused two separate line faults from lightning strokes. The magnitude of lightning discharges and rough location are shown in the figure 8. It can be seen that the first and subsequent discharges are 21kA & 11kA respectively.

Per DFR records, the first fault was phase B to C to ground and the second fault was phase B to ground only. 115kV line 73 is provided with dual overhead grounding shield wires. The typical 115kV NG line structure construction is shown in figure 8. The external and internal shielding angles are approximately 30 degrees, which are pursuant to the recommended shielding angles by IEEE Std. 998 - Guide for Direct Lightning Stroke Shielding of Substations.

For the line fault by lightning surges, the cause can be identified as direct lightning stroke or insulator back flashover. When the lightning discharges terminated on the overhead shield wires or directly on top of line structure, the significant amount of current would flow down the line structure and ground wires into the earth. Since the wave impedance of structure down lead is much higher than the normal working frequency values, the higher voltage rise over earth zero potential would be built up on the crossarm to which insulators are attached. When this overvoltage was more than the critical flashover voltage of insulators, the insulator flashover occurred and the line fault was formed. It was more likely that the first lightning stroke hit on the shield wire and the line fault was caused by insulator back flash on phase B & C insulators.

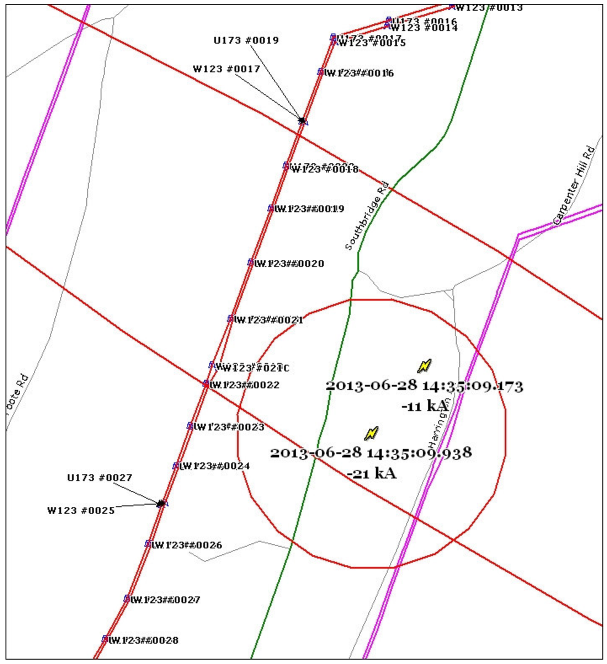

Figure 8: Lightning information from NLSN

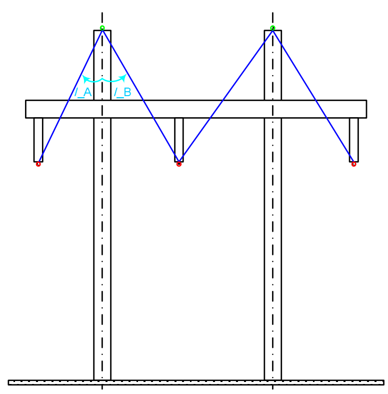

Figure 9: Typical 115kV line structure with dual overhead shield wires

Lightning strokes of low magnitudes (a few tens of kA) can bypass the overhead shield wire and can stroke directly on the phase conductor [5]. The magnitude of second stoke was only 11kA and it was very likely the second line fault on line 73 was caused by direct lightning stroke on phase B conductor. To confirm the suspect, an EMTP simulation was performed to verify the overvoltage stress at line structure insulator and breaker 73 B-phase main contact.

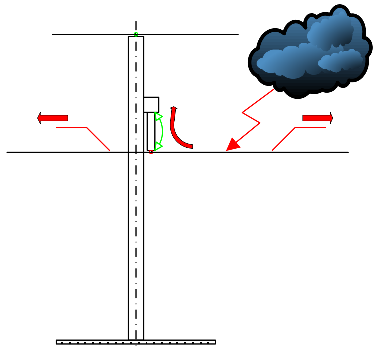

Figure 10: Direct lightning stroke on phase B conductor of line 73

3. EMTP simulation for the second lightning stroke on line 73:

3.1 Lightning discharges and standard mathematical modeling

In reality, the lightning discharge currents may differ in the amplitude and shape. The shape of the current wave and the corresponding voltage wave could be different for every stroke. To facilitate the study of lightning, the shape of the stroke wave is standardized in a 1.2/50-µs impulse waveform as specified in IEC standard 60060-1 High voltage test techniques. The 1.2µs front rising time is a virtual parameter which is 1.67 times the time interval between 30% and 90% of the peak value. The 50µs tail time represents a time point where the wave has dropped to 50% of the peak value. Figure 10 is the standard full lightning impulse from IEC standard 60060-1.

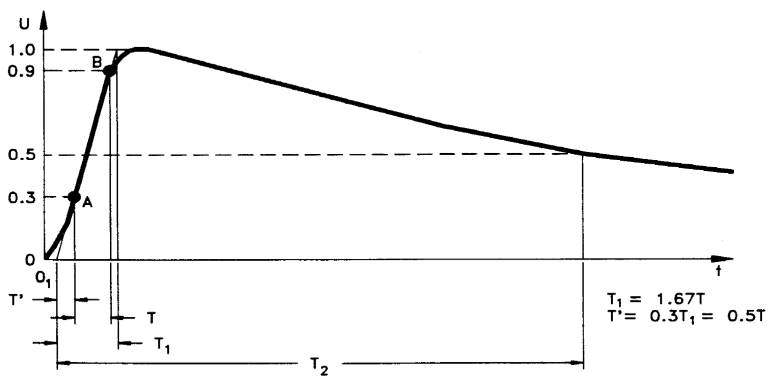

Figure 11: The standard 1.2/50-µs lightning impulse waveform defined in IEC standard 60060-1

When a lightning or switching surge current is introduced into the power system, the induced voltage wave by the surge current is determined by the characteristic impedance of the network where the surge travels. Basic Insulation Level (BIL) parameter of HV equipment specifies the maximum peak voltage that the equipment can withstand without the break down of the insulation. BIL is the standardized value for HV equipment at different voltage ratings. It should be noted that equipment with nominal voltage more than 245kV has Basic Switching Impulse Insulation Level requirement for slow front switching surges in addition to BIL for fast front surges.

In the computer simulation, the lightning surge can be approximated by dual exponential functions to emulate the standard fast front impulse:

$I_{test} = I\,(e^{-\alpha t} - e^{-\beta t})$

Where:

I=1.02 times of surge charge current

$\alpha = 1.4*10^4$

$\beta = 4.5*10^6$

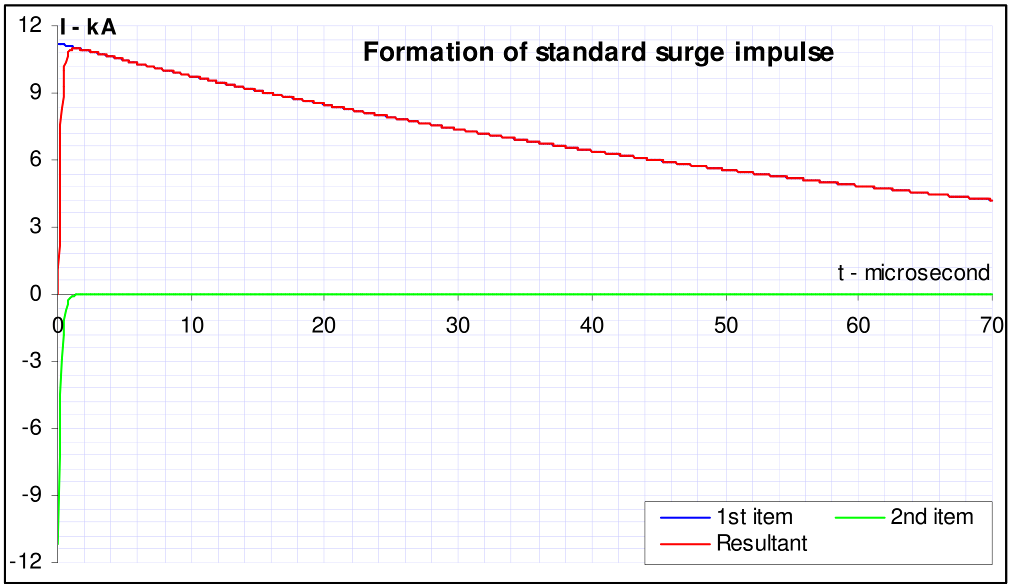

Figure 12: The approximation of lightning impulse by dual exponential functions

3.2 The modeling parameters of EMTP simulation under PSCAD/EMTDC program:

A simplified model was made for the second direct lightning stroke on 115kV line 73 in PSCAD/EMTDC program. A lightning surge with 11kA magnitude was introduced to B-phase conductor of line 73. To simplify the study, the lumped parameters were used for the different system components.

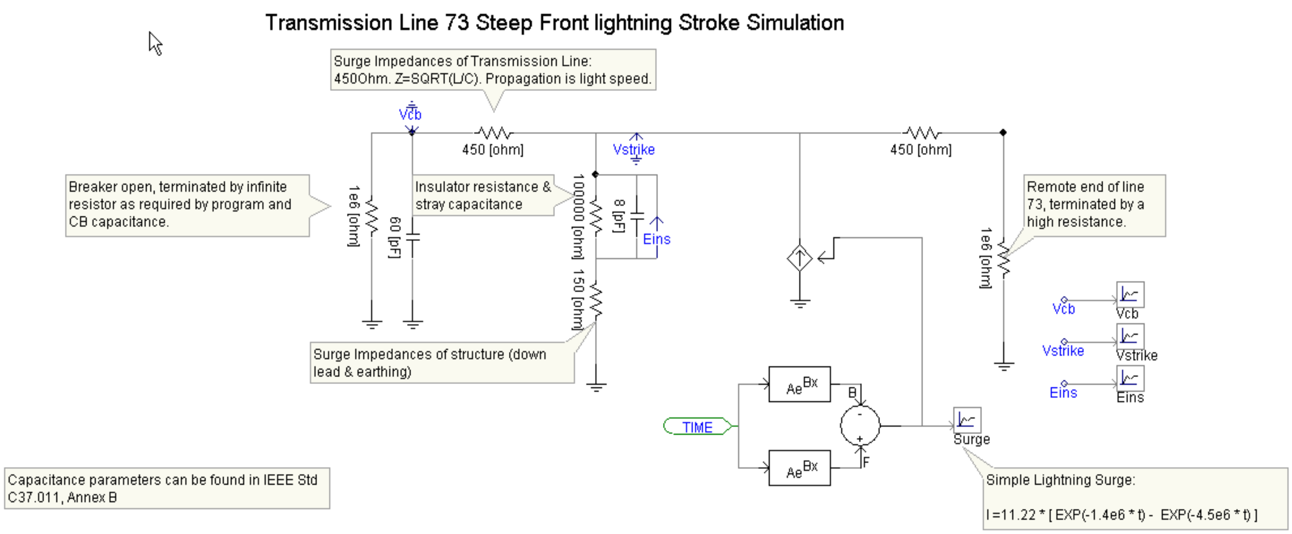

Figure 13: The modeling for the second lightning stroke simulation

The surge impedance of 115kV line 73 is calculated by the formula below:

Z=SQRT (L/C)

Where: L and C are the inductance and the capacitance per unit length of the line. The surge impedance has the nature of pure resistance, but it can't dissipate surge energy as the conventional resistor could. It also should be noted that the surge impedance of a line is constant for a certain type of line structures and remain the same with the change of line length. In the model, 450 Ohm is used for the line surge impedance.

When line 73 breaker is open, the breaker can be modeled with an infinite resistance and paralleled stray capacitance. The values of line insulator capacitance near direct stoke location and breaker bushing capacitance is selected from the typical value of IEEE std. C37.011. The down lead surge impedance of line structure at closest direct stoke location and tower grounding resistance are combined with 150 Ohms.

The voltages for the insulator string at the nearest direct stroke structure and breaker 73 at substation are monitored. The simulation was performed in PSCAD to find out the voltage distribution right after the stroke. From the simulation, it can be seen that the voltage on the line side of main contact of the breaker started to rise and the voltage gradually reached to approximately the peak 750kV which exceeded the BIL of this 115kV breaker. Because there were no lightning arrestors on the line side, the high surge voltage would not be clamped. It should be also noted that the bus side of breaker was still energized with 115kV. As a result, the SF6 gas insulation between breaker 73 B-phase contacts was broken down. The following figure 13 shows the typical interrupter of a dead tank breaker. When the fast front lightning surge arrived at the departed main contact on the line side, the very high electric fields were applied across dielectric material (SF6 gas) between breaker contacts and a number of electrons may be suddenly excited to form the conduction path.

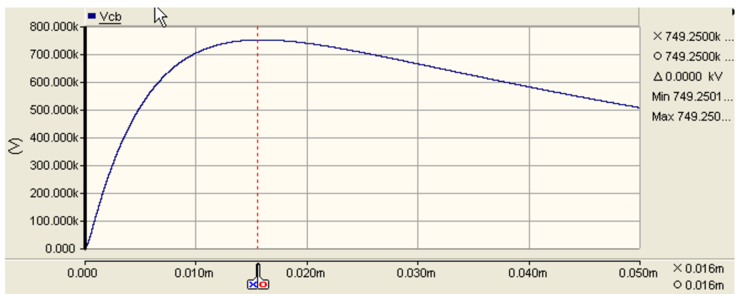

Figure 14: transient voltage on open state breaker terminal

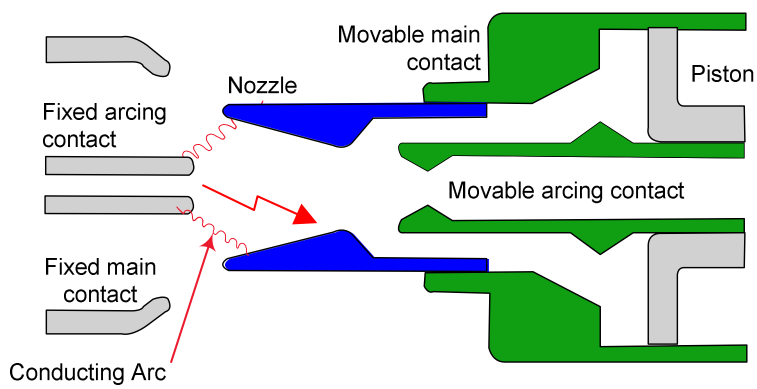

Figure 15: Interrupter of SF6 dead tank breaker at open contact position

Most likely the arc was initially developed between fixed arcing contact and the protruded nozzle when the surge voltage exceeded breaker BIL. With the presence of initial arc, the SF_6 molecules in vicinity were further ionized and then stable arc path was formed between the breaker main contacts until the source from Substation Carp was isolated by breaker failure protections. After the arc extinguish, the decomposed SF_6 from the arc under extreme high temperature can be recombined back to SF_6.

The voltage on the B-phase insulator of line structure which was the nearest to the direct stroke is shown in Figure 16. The maximum strain voltage over the insulator exceeded its BIL (550kV) and flashover was expected on the insulator, resulting in the B-phase-to-ground fault.

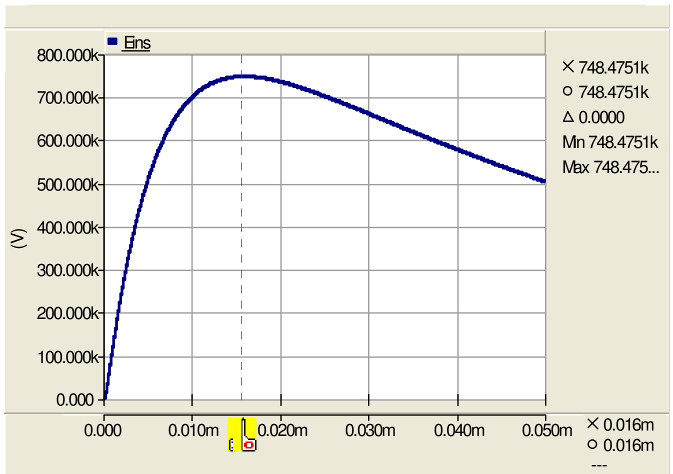

Figure 16: Voltage over insulator from the lightning stroke

Closing Thoughts

Briefly recapping we have learned the following:

- The 73 line protections operated properly on the first lightning stroke and successfully tripped the corresponding breakers to isolate the fault.
- The sudden pressure relay for the #1 transformer operated correctly due to tertiary winding movement during the first line fault.
- The 73 line protections correctly operated again on the second fault and initiated the 73 breaker failure protection due to the insulation breakdown of the breaker 73 B-phase main contacts even though the breaker was already in open status.
- The 73 breaker failure operation was proper to isolate the internally faulted condition of the 73 breaker.
- The 74 breaker failure operation was improper due to a latent design issue having to do with sharing of timing relays.

A key take away from the event is the critical role the digital fault recorder played in hypothesizing what had occurred and why. In a time synced format the DFR provided several key pieces of information including the initial 73 line fault, the autotransformer lockout and the second lightning stroke fault current and the various relay and breaker failure operations that followed. Fault current displayed through the DFR on the 73 line with breaker open status was vital information in uncovering the flash over occurrence inside the 73 breaker.

The EMTP simulations run to determine fault characteristics and the SFRA tests run on the autotransformer to detect winding status were excellent supplemental tools in validating the theories arrived at by the initial relay target reports and DFR data. As shown in this report despite the many complexities possible in a single disturbance concise conclusions can be reached utilizing the listed analysis tools and collaborating across inter utility disciplines.

Reference:

1. "Power System Relaying", (book), Stanley H. Horowitz, Arun G. Phadke
2. "Applied Protective Relaying", (book)
3. Doble transformer test reports for #1 transformer at substation Carp.
4. "High Voltage Circuit Breakers - Design and Applications", (book), Ruben D. Garzon
5. "Computer-Aided Power System Analysis", (book), Ramasamy Natarajan
6. IEC-60060-1 High voltage test techniques
7. IEEE Std. C37.011 - Application Guide for Transient Recovery Voltage for AC High-Voltage
8. Applications of PSCAD/EMTDC
9. HV circuit breaker manual by manufacturer

Yujie Irene Lu received a BSEE degree in Power Systems Engineering from Huazhong University of Science & Technology in China, and a MSEE in Electrical Engineering from Virginia Polytechnic Institute in Blacksburg, VA. She is a senior member of IEEE and a registered professional engineer in MA. She received the 2010 Outstanding Engineer Award from the Boston Chapter of the IEEE Power and Energy Society in November 2010. Irene has been employed in Protection Engineering at National Grid since 1990. She is a principal engineer in the Department of Protection Policy and Support, where she analyzes system disturbances, performs system analysis for short circuit conditions, develops protection and control system standards, designs protection systems on a conceptual basis, specifies equipment and determines protection settings and logics. She has 20 year's experiences as a lead protection engineer on projects and worked on installation of major 345/115kV GIS transmission substations. Irene has represented the National Grid as a standing member of NPCC TFSP (Task Force on System Protection) and SP-7 (System Protection Misoperation Review working group) since 2011. Previously, Irene worked for the Department of Energy of China for 5 years

Song Ji is a lead senior engineer in the Department of Protection Policy and Support of National Grid, where he analyzes system disturbances on transmission and supply networks, develops & reviews protection related standards. Song has more than 16 years experience in the power system studies, substation & power plant design, protection and control for utility and industrial systems ranging from 4.16 kV to 500 kV. Prior to joining National Grid, Song spent 4 years with Worley-Parsons Canada as a power system specialist and 9 years with Henan Electric Power of China State Grid as a power system engineer. He received BSEE in power system from Zhengzhou University in China and a MSEE in power system from Royal Institute of Technology in Sweden. He is a member of IEEE and a registered professional engineer in Alberta Canada.

Scott Slaski has been with National Grid for 4 years, 2 as a test technician and 2 as a supervisor in the Protection Operations department whose responsibility it is to install and maintain the relay and fault recording equipment in the National Grid substations mentioned in this report. Prior to joining National Grid Scott worked for Vermont Electric Power Co. for 3 years as an electrical test technician. Scott has an AAS in Electrical Engineering Technology.