Lesson Learned

Transient Induced Misoperation: Approach II (Loss of Protection during Severe Lightning Event)

Primary Interest Groups
Transmission Owners (TOs)
Generator Owners (GOs)
Transmission Operators (TOPs)
Generator Operators (GOPs)
Reliability Coordinators (RCs)

Problem Statement
System 1 and System 2 protection groups shut down as a result of a lightning-strike-induced fault at one terminal of a 345 kV transmission line. Neither System 1 nor System 2 local relay protection cleared the fault. The fault continued for over 1.5 seconds until protection at the remote terminals tripped as designed via time-delayed elements.

Details
A 146 kA magnitude lightning strike[1] occurred near a 345 kV line and terminated at a 345/115/13.8 kV substation. This strike caused a backflash on a 345 kV line structure just outside the station, resulting in a B phase-to-ground fault.

This fault was not cleared by the local station System 1 or System 2 line protection relays as they both powered off and rebooted seemingly simultaneously with this strike. The System 1 protection scheme uses directional comparison blocking (DCB) via power line carrier, and the System 2 uses line current differential via optical ground wire (OPGW). The protection systems utilize different relay manufacturers and are supplied by separate DC systems. The System 1 protection at the remote terminal of the faulted line operated via the DCB communication-assisted elements in 4.5 cycles. The remote System 2 line current differential did not operate due to the loss of communication with the powered off relay.

However, since the fault was left uncleared at the local station, 14 remote 345 kV and 115 kV terminals operated for the fault via neutral time overcurrent (TOC) or over-reaching step distance protection elements to clear the fault. Total clearing time for this 345 kV Single Line to Ground fault was approximately 1.5 seconds. All lines reclosed as designed. A one-line diagram is included on the following page (**Figure 1**).

There were no System Operating Limit (SOL) violations or transmission security issues that resulted from this event due to the favorable system conditions at the time. However, post-event studies showed that the consequences of a simultaneous failure of both line protection systems under more stressed conditions could potentially result in an Interconnection Reliability Operating Limit (IROL) violation. To mitigate this risk, the TOP and RC worked together to develop a temporary operating guide that required

[1] The average lightning strike strength in the service territory is approximately 30kA.

opening the affected 345 kV line terminal breakers if lightning was detected within 20 miles of the station. This operating guide remained in effect until corrective actions were completed.

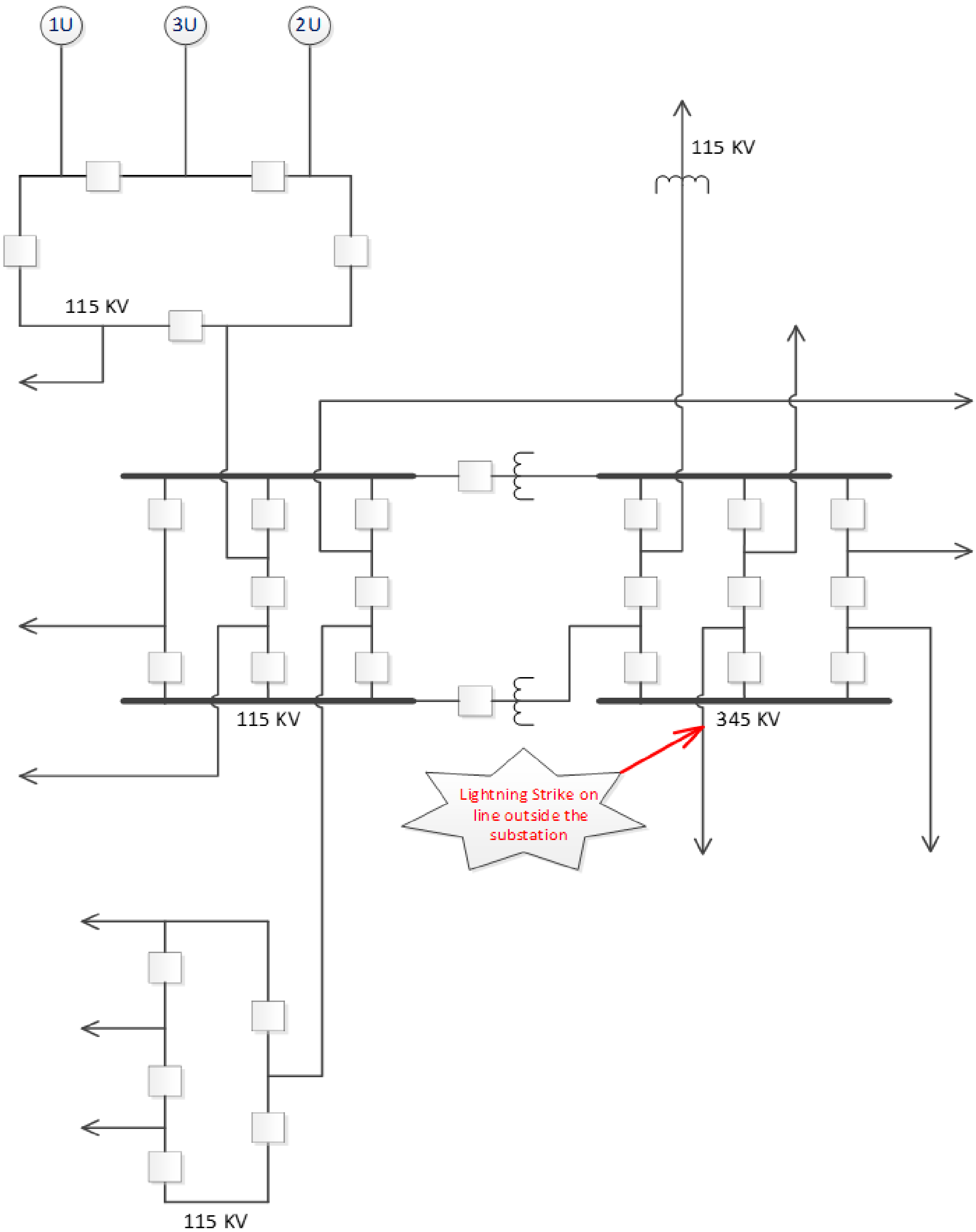

Figure 1: One Line Diagram

The System 1 and System 2 line relays that rebooted contained no event records, and there was no indication that protection elements within the local relays picked up at the time of the lightning strike. The relays provided no obvious indicator as to the cause of their reboot. Sequence of events recorders in each relay captured their respective powering on seconds after the fault was cleared. The relays then remained in service until removed and were returned to the respective manufacturers for further testing. It was later discovered by the manufacturer of the System 1 relay (to be referred to as Manufacturer A) that the relay was found to have a failed contact input with visible burning on the circuit board surface.

Damage to the circuit board trace was also visible only under x-ray microscope. No physical damage was found with the System 2 relay (Manufacturer B).

Additional equipment at the station incurred damage. These are listed as follows:

- A 115 kV line relay that rebooted (like the affected 345 kV relays)
- Security camera equipment in the control house
- A multifunction meter
- Several EIA 232 to 485 communication port converters failed on various relays (used for remote access)
- Distribution power line carrier communication equipment located in cabinets in the 13.8 kV yard

It became evident that both dc systems were affected by this strike. The digital fault recorder (DFR) system from the station showed that, the digital input channels all picked up very briefly at the inception of the fault (for a time recorded by the DFR as 500 µs–sampling frequency of the DFR is 7,680 Hz). Most of the actual devices wired to these DFR channels did not actually operate. This momentary assertion captured by the DFR was the first indication that the dc systems were subject to impulses likely caused by the lightning strike.

The initial findings suggested that a significant surge was impressed on the equipment in the control house, resulting in the relay reboot. Subsequent to the event, a systematic testing and station design verification was performed on the station.

Investigation, Testing and Analysis

Both the System 1 and System 2 relays, which rebooted due to the lightning strike, were sent to their respective manufacturers for forensic analysis. Both manufacturers were asked to conduct similar factory acceptance tests with an emphasis placed on the surge withstand specifications of each relay.

Each manufacturer maintained that their product was built and tested to the latest IEC 60255-26 (2005) and IEC 61000-4-5 (2005) standard at the time of manufacture. The surge withstand test consists of 50 µs pulses of various high voltages and of positive and negative polarity to the terminals of the power supply. The power supply under test was originally designed for up to 2.0 kV surge withstand. The standard was updated in 2013 increasing the surge withstand to 4.0kV.

Relay manufacturer A (System 1) subjected the power supply and spare undamaged inputs on the actual System 1 relay and a replica up to surges of 8.0kV. It should be noted that surge withstand testing is destructive. Manufacturer A was unable to recreate the relay damage and reboot based on surge withstand testing in their facilities. Subsequent testing was undertaken by Manufacturer A at a third-party facility with the capability of producing higher test voltages than what were used in initial testing. The relay power supply no longer operated as designed after the test at 6 kV. Testing at 8–40 kV was completed without power to the unit, and damage to the contact input circuitry was observed. Manufacturer A postulated that it is possible that the relay could be affected in different ways by different voltage levels and impulse characteristics that resulted in the observed behavior, but the relay under test did not reboot under these test conditions.

Relay Manufacturer B (System 2) was able to recreate the failures in their lab during surge withstand testing on both the actual System 2 relay and a replica when the relay was subjected to a 4.0 kV surge (see **Figure 2**). Manufacturer B concluded that the ground potential difference exceeded the surge withstand capability of the relay, resulting in a reboot.

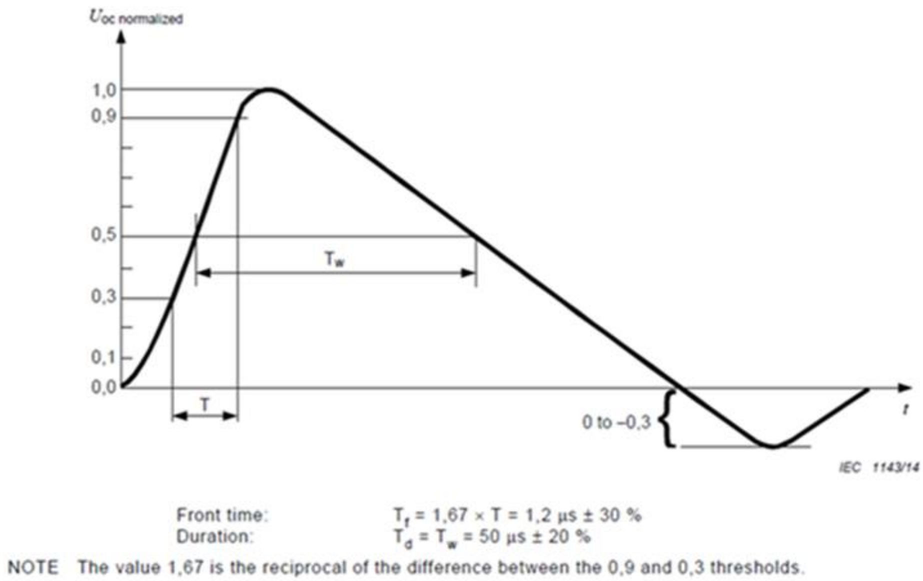

Figure 2: IEEE Surge Withstand

The protection relays that rebooted as a result of this event were installed in 2011 and therefore met the 2005 standard.

Testing was performed to validate the integrity of the station ground grid to determine if it contributed to the loss of protection. The results showed that the integrity of the ground grid was adequate and constructed as designed. Results from ground grid testing validated ground grid resistance and soil resistivity used in the transient simulation of the event. This is discussed as follows.

Evaluation of System Design

The configuration of the impacted station evolved over the past 50 years. It was originally designed with only electromechanical relays and unshielded control cables. As substation upgrades and modifications were installed, each modification was made with the specification of that time and only impacted systems were upgraded. This led to the existence of different cabling design practices within the impacted station.

A comprehensive survey of the characteristics of the low voltage control cables from all devices in the switchyard was conducted. This survey revealed a mix of unshielded control cables, shielded control cables with the shield grounded on only one end (in the control house), and Capacitor Coupled Voltage Transformer (CCVT) control cables with the shield grounded on both ends.

The resulting survey information for the switchyard cabling was provided to a company recognized as having expertise on grounding, electromagnetic interference, and electric transient analysis. The company was asked to conduct a station grounding study with an emphasis on the ground potential rise/ground potential difference (GPR/GPD) caused by the lighting strike and the resulting transient voltages at the end of low voltage control cables terminal ends, relative to ground, at the relay panels.

Simulations of the event were created to predict the transients experienced in the control house measured at the conductor ends to relay case.

The first case study modeled the station cabling arrangement at the time of the event, both shielding and grounding. For this case, the maximum GPD was about 100 kV peak-to-peak and remained excessive for 50 microseconds. The results demonstrated the high transient voltages experienced by the equipment in the station control house. Although not replicated here, it is noted in the report that the maximum stress GPD values would be in the order of 60 kV peak-to-peak for much lower soil resistivity values of 600Ω-m, still an exceptionally high value.

The second case study modeled the station with the control cables shielded and shields grounded on both ends. A simulation was run to determine the level of GPD transient experienced in the control house at the cable ends. The results of this simulation indicate that the GPD magnitude at the control house equipment would be around 3 kV peak-to-peak for the configuration with the control cables shielded and grounded on both ends. This would have been below the current surge withstand rating for the relay manufacturers utilized.

In addition, the simulation showed that the ground grid design had little impact on the voltage transients seen by the protective relaying during the lightning event.

Corrective Actions

As a result of this event, several short- and long-term corrective actions were undertaken.

Control cabling of the faulted line was upgraded with shielded cable that has been grounded at both ends. The cabling was also rerouted to achieve physical separation from the yard devices into the control house.

All damaged relays and equipment listed above was replaced and recommissioned.

The Bulk Electric System portion of the impacted station has been prioritized for capital investments to upgrade all remaining cabling with shielded cable that is grounded at both ends.

A survey of all significant BES stations within the area was conducted to determine where outdoor station equipment exists with unshielded control cables and cables with shields grounded at only one end. These stations have been targeted for future capital investment upgrades based on risk level.

Lessons Learned

- The protection system owner must consider the surge withstand rating of the equipment being installed when developing the associated wiring and cable shielding designs.
- Careful attention to proper shield grounding methods is critical to reduce the effects of ground potential differences due to system transients. This becomes more important with long cable runs

as ground mats may deteriorate over time or be separated due to distance (common in cases of generation station to switchyard runs).

- Protective relay systems, when exposed to surges beyond their specified criteria, may not operate as intended or fail as expected. Relay system end users should be made aware that there are ramifications to exceeding design specifications beyond relay damage and failure, such as a reboot that can result in total loss of protection at the time of the event. Proper consideration should be given to using all available self-monitoring to alarm for these conditions and failure modes.
- When additions or modifications are made within a substation, the affected cabling should be upgraded to comply with the latest cable design practice. Evolving station designs with different cabling design practices may result in reduced dependability of microprocessor-based protection systems.

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