NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Lesson Learned

Protracted Fault in a Transmission Substation

Primary Interest Groups
Transmission Operators (TOPs)
Transmission Owners (TOs)

Problem Statement
Electronic communications equipment utilized to transmit and receive information from the remote terminals of a transmission line automatically shut down within milliseconds when a bus fault occurred at one terminal of the line. Neither the primary nor the back-up relay protection cleared the fault. The fault continued for over four minutes.

Details
A single-phase-to-ground fault occurred on an instrument voltage transformer connected to the bus section that serves as the transmission line's terminal at Substation 1. The instrument voltage transformer was a capacitive coupling voltage transformer (CCVT)[1], comprised of a stack of coupling capacitors that form a voltage divider that supplies approximately 5 kV to a small potential device that in turn steps down the voltage to 120 volts for utilization by metering and back-up protective relaying. (See **Figure 1**). This instrument voltage transformer had exhibited low, out-of-tolerance output prior to the event. Low output voltage is often thought to be a benign condition for coupling capacitor devices.[2] The output to metering and back-up relaying had been temporarily isolated prior to the event to preclude false readings and avoid the risk of relay misoperation, but the coupling capacitors remained connected[3] to the transmission bus.

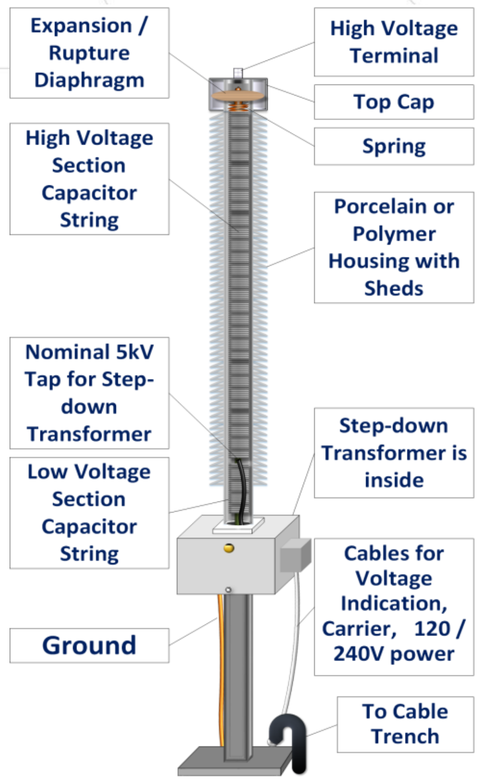

Figure 1: Typical CCVT

Communications equipment shut down at the substation where the fault occurred because of an electrical transient associated with the fault. The communication channels carried information utilized by the line differential relaying essential to the protection of the line and the bus sections at the line terminals.

[1] CCVTs are one of the 14 common substation equipment types listed in the NERC Event Analysis' "Addendum for Events with Failed Station Equipment" for capturing failure modes and mechanisms in reported events.
[2] When capacitors begin to fail in a CCVT, it is usually by shorting out of individual capacitor packs in the string. If packs short out above the CCVT's "low voltage tap," the output voltage rises. If packs below the 'low voltage tap' short out, the output voltage would lower. In either case, there would be increased voltage stress across all the remaining capacitors in the string, accelerating their failure. As long as the string remains energized, this leads to a continuous sequence of shorting packs out and eventual catastrophic failure. Monitoring the output for "stair steps" can warn of a developing failure.
[3] The isolated output meant the condition of the capacitor string could not be monitored for the developing failure. It would have been better to remove power from the capacitors too. The difficulty of getting clearances for equipment that is expected to be "always on" contributed to leaving the equipment in this state for a long duration.

The transient, coupled to a 125-volt DC battery supply circuit in the substation by induction, activated a shutdown feature built into the electronic switching power supplies of the communications equipment. This feature was intended to protect the communications equipment against internal overloads on its printed circuit boards, chassis, and internal wiring. However, in this case, there was no internal overload. The shutdown feature misoperated in the presence of the transient because it carried an electrical or electronic signature similar to a bona fide overload condition within the communications equipment.

The instantaneous loss of communications prevented the line differential relaying from properly detecting the fault, so it blocked tripping by design. Stand-alone back-up relaying at the local substation where the fault occurred was temporarily out of service due to a problem with an instrument voltage transformer circuit. Stand-alone back-up relaying at one of the remote substations was slow in detecting the fault for several reasons, listed here:

- The line includes a series reactor with significant impedance (seven times more than the line impedance itself) for limiting fault current so as not to exceed interrupting capability of the circuit breakers. The impedance posed a challenge to setting the distance relay elements to ensure they did not over-reach to the next substation.
- The ratio of the impedance presented by the transmission line to a phase fault versus a ground fault is very different from the ratio presented by the series reactor. This results in the combined circuit (line and reactor) having an overall impedance that is non-homogeneous, posing another challenge to setting the distance relay elements.
- The fault evolved from a single-phase-to-ground fault to a three-phase-fault, then to a double-phase-to-ground fault, and finally back to a single-phase-to-ground fault. This evolution resulted in ground and phase distance elements alternately picking up and dropping out during the course of the event.

Figure 2 depicts the three-terminal transmission line involved in the event. One of the two redundant lines of primary line differential relaying is shown in a simplified format, including the communication equipment at two of the terminals. The third terminal is not included in the diagram for the sake of simplicity.

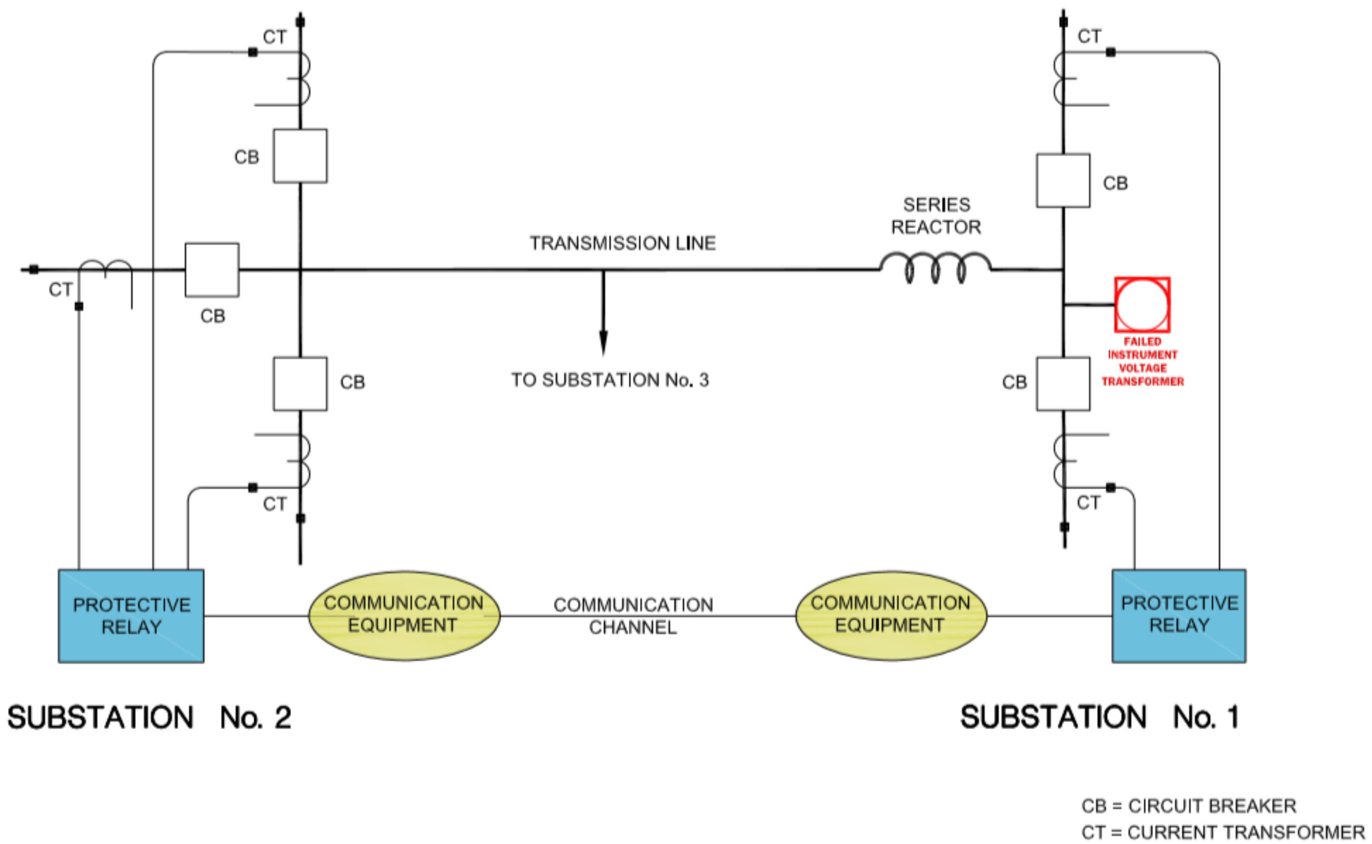

Figure 2: One Line Diagram of Faulted Circuit and Line Differential Protection

The fault was not cleared by either the primary or the back-up relay protection. It was determined from digital event files within the protective relays that communications between the relays for this circuit ceased simultaneously with the inception of the fault. Specifically, all four multiplexers associated with the line protection at Substation 1 had automatically shut down. The multiplexers are integral to the communications. They convert signals from the relays to a format suitable for transmitting over the digital telephone networks. **Figure 3** depicts the redundant double-triangular arrangement of the communication channels – Routes 1 and 2 – spanning all three terminals of the transmission line. It can be seen that each protective relay utilizes two multiplexers, one to connect to each of the two other substations.

The multiplexers were powered down even though their power switches were found in the ON position, and the 125 volt dc supplies from substation batteries were not interrupted. Each of the four multiplexers has two internal and independent electronic power supplies for the sake of redundancy. All eight internal electronic power supplies shut down automatically, which is the proximate cause of the loss of digital communications.

NOTE: If only one of the eight power supplies in the four multiplexers at Substation 1 had not shut down, the fault would have been cleared in normal high-speed fashion because the signals to and from Substation 1 would be exchanged with either Substation 2 or 3 as long as one route of communication remained between Substation 1 and either of the other two substations and then retransmitted between Substations 2 and 3, completing the triangular communications.

After the event, all eight of the power supplies were able to be restarted simply by manually cycling their power switches from ON to OFF and back to ON again. The multiplexers then resumed functioning, and normal communications were restored. There was no visible or functional damage to the multiplexers whatsoever. Neither the impacted electric utility nor the manufacturer is aware of this issue occurring prior to this event. The multiplexer equipment has a good track record of performance in the industry world-wide for many years.

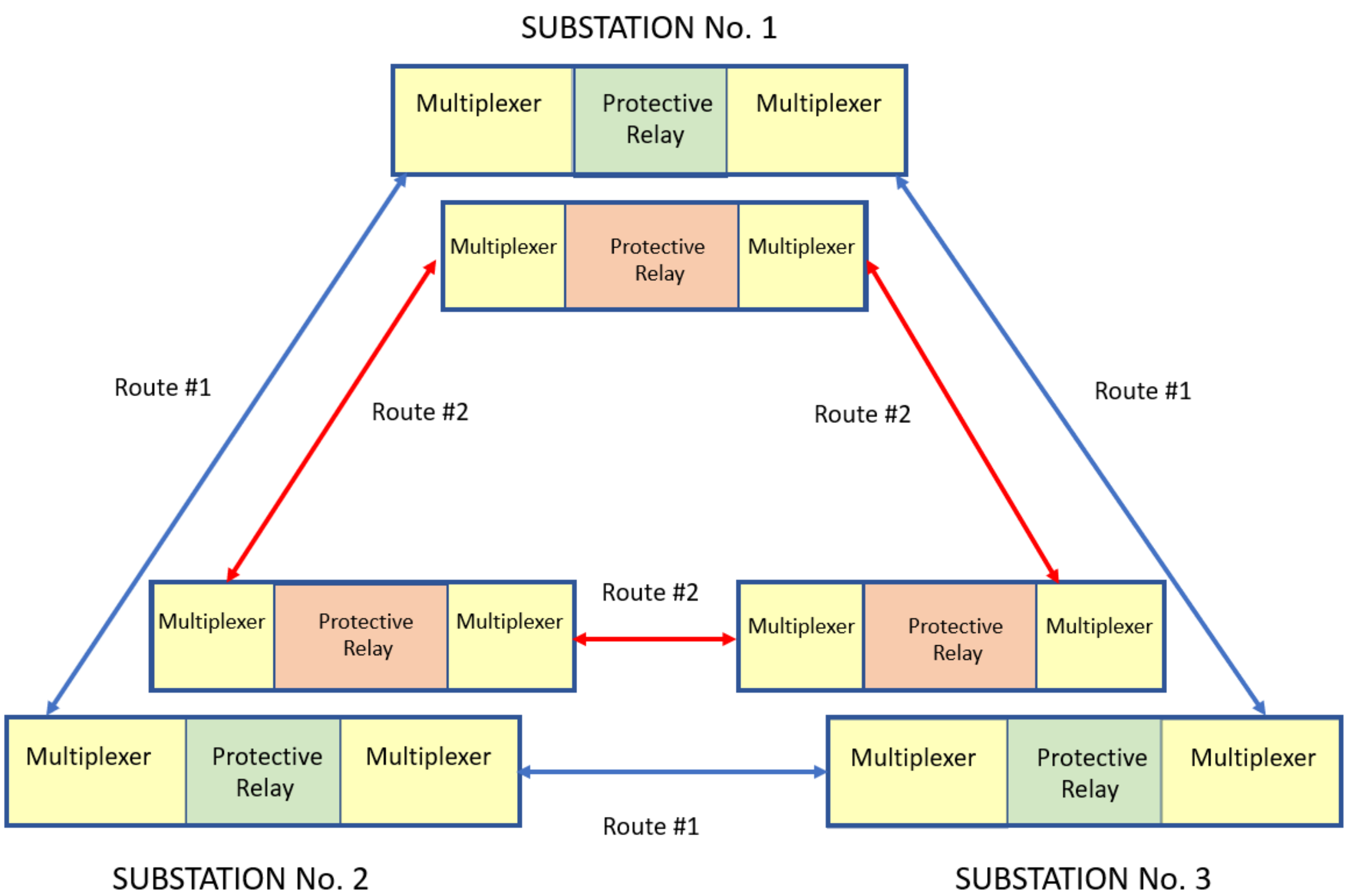

Figure 3: Redundant Communications for Three-Terminal Line

The shutdown was the result of activation of a control scheme on each power supply's printed circuit board that was intended to protect the power supply from overloading in the event of a short circuit within the multiplexer chassis or on any of its printed circuit boards, including those serving the communications functions. The scheme, when activated, inputs a signal into the integrated circuit chip that controls the switching cycle of the power electronics that simply stops the switching and holds it off until the power supply is manually restarted by toggling its ON-OFF rocker switch.

By design, the primary current differential relaying inhibited tripping when communications were lost. The loss of digital communication was simultaneous with the fault. Inhibiting tripping when communications are lost is necessary to prevent false tripping because the differential relays are unable to compare the current flowing into the transmission line at one end to the current flowing out at the other end without communications.

As previously mentioned, an electrical transient generated by the fault on the Substation 1 bus section was coupled into the 125 volt dc battery supply circuit to the multiplexers. The exact mechanism of this coupling from an AC transmission fault into a dc supply circuit is not known. It was recognized, however, that the dc supply circuit was routed a considerable distance (~1000 feet) in substation trenches and cable trays shared with ac control wiring. It is typical the shielding is interrupted when cables enter and leave junction boxes. This offers a possible path for coupling by induction.

Another area that is typically of concern when problematic transients are generated by switching surges, lightning, or faults is substation grounding. Post-event testing revealed that the continuity between two adjacent ground grids in the affected area–one where the multiplexers reside and the other where the fault occurred–was less than desirable. This may have resulted in a more severe electrical transient being imposed on the multiplexer.

Post-event testing succeeded in recreating the shutdown scenario by selective switching on the power system. During this testing, a transient was captured that was subsequently reproduced by a signal generator and applied to the multiplexer power supplies, resulting in their shutdown. The electrical signature of this applied test transient waveform was different from those specified in the IEEE C37.90 standard for surge withstand capability. The standard includes both an oscillatory and fast transient test waveform. The test transient that resulted in the shutdown of the multiplexers was lower in amplitude and had a slower rate-of-rise than the IEEE waveforms but was of a longer duration. Thus, it fell outside the bounds of the standard. The multiplexer was designed to withstand the IEEE waveforms, and successfully passed when subjected to these waveforms.

Figures 4–7 show some of the damage that resulted from the event.

Figure 4: Failed C Phase CCPD

Figure 5: Damaged B Phase CCPD

Figure 6: Remnants of Bus Insulators

Figure 7: Exterior of Relay House Singed by Protracted Fault

Corrective Actions

All equipment damaged at Substation 1 during the fault was replaced. This included the instrument voltage transformer for the stand-alone back-up relaying that had been temporarily out of service.

The routing of the 125 volt DC supply feeds to the multiplexers that shut down during the event at Substation 1 has been significantly shortened, bypassing the long runs in control wiring trenches across the substation yard.

The ground grids at the affected substations have been reinforced.

An extent of condition review was conducted system-wide to identify locations where the type of multiplexer that shut down during the event is utilized for both the first and second line protective relaying. A fast-track effort was then embarked on to replace the power supplies in all of these multiplexers (two each) with power supplies that had been modified by the manufacturer to disable the shutdown scheme.

This was based on the underlying premise that it is preferable to sacrifice the power supplies within a multiplexer that develops an internal overload than to incorrectly shut down the unit and consequently disable a communications channel vital to the protective relaying. In addition, for all of the transmission lines associated with the substations involved in the event, the multiplexers on one of the two lines of communication for every transmission line were replaced with new units of a different design and from a different manufacturer for the sake of diversifying the communications.

Going forward, all new and upgraded installations will utilize relays and communications equipment (multiplexers included) from different manufacturers for the first and second line protective relaying. This diversity of suppliers for redundant equipment is fundamental to the philosophy and design basis for protective relaying systems on transmission facilities.

Modifications of the stand-alone back-up relaying ensure coverage of the entire circuit with adequate margin so that the whole line, including any intermediary equipment, is sufficiently protected.

Lesson Learned

- Equipment that is out of service for maintenance, repairs, or replacement should be completely isolated. The maintenance, repair, or replacement work should then be conducted as quickly as possible to minimize potential compromises to system reliability.
- Control wiring routing and shielding should be designed to minimize the possibility of the coupling of transients between adjacent circuits.
- The functions served by protective relaying systems (including associated communications) are critical to the reliability of the transmission system. These functions, therefore, must have priority over schemes intended to monitor and react to problems internal to the individual components (e.g., electronics) that comprise the protective relaying systems. It's preferable to sacrifice an internal component than to have the protective system fail during a fault on the transmission system.
- Efforts should be made to have diversity in both the design and manufacture of all aspects of the protective relaying systems, including communications.
- Stand-alone back-up relaying must fully cover its intended protected zone with adequate margin for all types of faults.

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For more Information please contact:

NERC – Lessons Learned (via email)	NPCC – Event Analysis
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