NERC
NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Lesson Learned

Multiple Faults in Rapid Succession Contribute to Relay Misoperations Leading to Loss of Load

Primary Interest Groups
Transmission Operator (TOP)
Transmission Owner (TO)

Problem Statement
Four separate faults occurred in rapid succession in a bulk power substation as a result of weather-induced salt contamination. Relay misoperations in the presence of the faults resulted in loss of load.

Details
All four faults developed within a time span of 23 seconds as flashovers of support insulators and were single-line-to-ground faults all on phase C. Each fault was cleared properly in normal high-speed fashion by bus differential relaying and circuit breaker tripping. However, misoperation of protective relays on other transmission facilities during the faults tripped non-faulted lines connected to the substation, ultimately leading to a loss of load.

Damage was minimal due to the flashovers occurring on the insulator surfaces, allowing the equipment to be restored to service. Most transmission facilities and all loads were restored within 33 minutes.

The flashovers were caused by salt contamination on the surfaces of disconnect switch support insulators in a waterfront substation on the banks of a saltwater channel. A tropical storm had swept through the area two days prior. Before the storm left the area, its rain stopped completely and the wind direction shifted dramatically so that salt spray from the churning waters in the channel near the time of high tide was carried over the substation equipment without any rain to wash it off. This created a thin film deposit of essentially dry salt on insulator surfaces. In the absence of humidity or rain, the layer of contamination did not compromise the dielectric strength so no flashovers occurred on the day of the storm itself.[1]

When a light rainfall began later in the week, the four flashovers occurred. These flashovers happened during a critical wetting period before sufficient rain had fallen to wash the thin salt film off the surfaces.

The following relay misoperations prompted by the above faults resulted in load loss and are detailed in the next few paragraphs:

- A breaker failure relaying scheme incorrectly registered one breaker closed and tripped the adjacent bus section and the transmission line connected to it.
- A back-up relaying scheme used to protect a Phase Angle Regulator (PAR) did not have a proper polarizing source.

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[1] See NERC Lesson Learned LL20210801 "Insulator Flashovers Due to Combination of Salt Spray Deposits Followed by Light Rainfall Initiating Loss of Load"

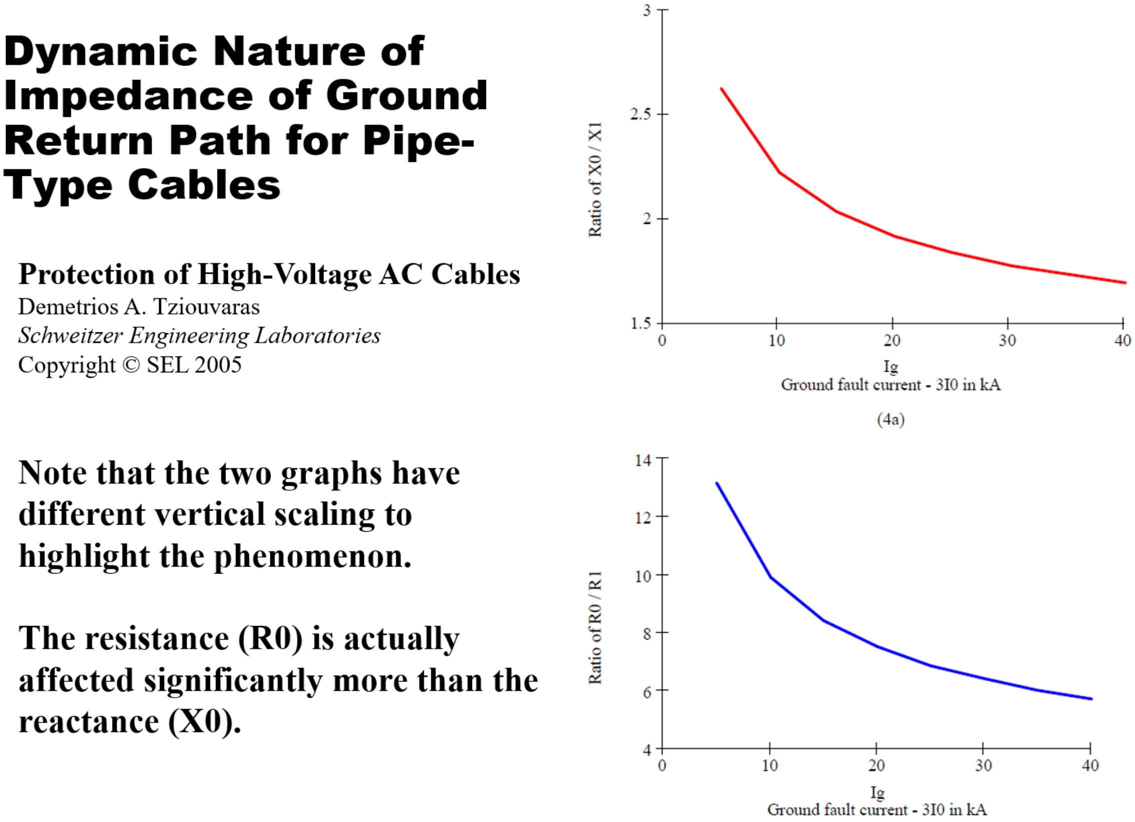
- Saturation of an auxiliary CT caused inaccurate input to a line differential relaying circuit, resulting in tripping of the associated transmission line.
- Overreaching of the Zone 1 ground distance elements occurred in the stepped distance relaying scheme that serves as backup to the line current differential relaying for two terminals remote from the fault location.

During the first of the four faults, a breaker failure relay scheme acted improperly. The scheme utilized current sensing to determine whether the breaker had opened and to supervise the associated timer. Normally, current sensing is considered superior to using the breaker's auxiliary contacts to detect breaker status because those contacts can become misaligned and may not reflect the status of the main breaker contacts. Typically the current sensing and the timing elements of breaker failure schemes reside in the same relay. Because this scheme combined upgraded relaying with a legacy timer, the current sensing element and the timer resided in separate relays. The current sensing element supervised the timer via contacts of an auxiliary output relay that was connected to the timer by control wiring. The auxiliary output relay was stuck in the closed position because its metallic contacts had become tack welded together. A contributing cause to the contact welding was the fact that load currents had been fluctuating around the current setpoint used to ascertain if the breaker was open or closed, so the auxiliary output relay was frequently opening and closing. When the first of the four faults occurred, the breaker failure relaying scheme incorrectly registered one breaker still closed and tripped the adjacent bus section and the transmission line connected to it even though the bus differential relaying detected it and the breakers tripped properly.

The second misoperation during the first fault was attributed to a back-up relaying scheme used to protect a PAR. The PAR had two lines of current differential relaying and the back-up scheme was not required. The back-up scheme was left in place to provide sensitive detection of certain low-level faults in the PAR windings. It was part of the same multifunction microprocessor relay package that included the differential relaying. The back-up scheme utilized directional overcurrent elements that depended on polarizing voltage to determine the direction of the current. A proper polarizing source wasn't available at the time of commissioning some months prior. A new bushing potential device had been procured for this purpose, but was not yet installed at the time of the event. In the meantime, it was presumed that the back-up scheme was automatically disabled (blocked from tripping) by virtue of it not having a polarizing voltage source connected. This was a misunderstanding of the relay logic. In fact, the scheme was still enabled and armed to trip as a nondirectional overcurrent element and therefore prone to tripping during faults external to the PAR.

The third misoperation occurred during the second of the four faults. An auxiliary current transformer (aux CT) saturated on the bus section adjacent to the fault location. The bus section served primarily as a line position, but line protection is complicated by a reactor located on the bus. The line differential relaying protecting that transmission line included current sensing from the shunt reactor aux CT. Testing after the event indicated that the aux CT was faulty, saturating at 42 volts versus the specified 400 volts. Saturation of this aux CT caused inaccurate input to the line differential relaying circuit, resulting in improper tripping of the associated transmission line.

Two additional transmission line trips associated with the four faults occurred due to relay misoperations at the remote terminals of the lines at a substation several miles away. After analysis, these have both been attributed to overreaching of the Zone 1 ground distance elements in the stepped distance relaying scheme that serve as backups to the line current differential relaying. The Zone 1 elements were set for 80% of the line impedance, yet they operated for faults at the substation at the remote ends of the lines, fully 100% away in terms of line impedance. It has been determined that the relays overreached because of the dynamic nature of the zero-sequence impedance of the transmission lines. These are underground lines housed in steel pipe-type cables. Magnetic saturation of the steel pipe in the presence of high fault current levels is a known phenomenon that results in changes in the impedance of the return path of ground fault currents. This is depicted in Figure 1, showing both the reactive and the resistive components with the latter exhibiting much wider variation.



Dynamic Nature of Impedance of Ground Return Path for Pipe-Type Cables

Protection of High-Voltage AC Cables
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Note that the two graphs have different vertical scaling to highlight the phenomenon.

The resistance (R0) is actually affected significantly more than the reactance (X0).

Figure 1: Ratios of Zero to Positive Sequence Reactance (top, red) and Resistance (bottom, blue)

Saturation was accounted for in the zero-sequence impedance model used to determine the relay settings, and appropriate compensation factors were applied. However, multiple faults in rapid succession, compounded by the transmission line trips previously described, fragmented the transmission system in the vicinity during this event, altering the fault current flows anticipated in short circuit studies. The impedance of the ground current return paths used in the modeling no longer matched the evolving conditions. Exacerbating the situation was the complex nature of the return current paths, including underground steel infrastructure such as water pipes, structural steel in tunnels and building foundations, etc.

Corrective Actions

- The breaker failure scheme comprised of current sensing to determine if the breaker has opened and a separate timer will no longer be used going forward. These two functions will be integrated into the same relay as is generally the case. The installation that resulted in the misoperation during this event was atypical.
- The PAR protection has been corrected by installing the proper polarizing source.
- The faulty aux CT that saturated has been disconnected. The approach has been modified to eliminate the need for the aux CT altogether. Rather than subtracting out the shunt reactor current from the line differential zone of protection, the line differential settings have been desensitized to tolerate the natural imbalance introduced by the shunt reactor current. Adequate margin was available to permit this change because of high fault currents in the relevant portion of the transmission system.
- The zone one elements of the stepped distance back-up relaying on the underground pipe-type cables have been put on standby to be armed only when the communications used by the line current differential relaying are unavailable. This will be done automatically so that if communications are suddenly and unexpectedly lost, the zone one elements will immediately begin protecting the lines.

Lesson Learned

- Interconnecting old and new protective relays can introduce unforeseen problems. As noted in the Details section of this document, a breaker failure relaying scheme consisted of a legacy timer supervised by the current sensing element of a newer relay that had been installed as part of a relay upgrade project. Thus, two functions (i.e., the current sensing and the timing) that would typically be included in a single device in a new installation resided in separate devices that needed to logically be linked to one another via an auxiliary output relay and control wiring. The auxiliary output relay, a mechanical component, took the place of internal electronic logic to accomplish supervision of the timer by the current sensing element, and it was the mechanical failure of the auxiliary relay's output contacts that led to the misoperation. For another discussion on mixed relay issues, see NERC Lesson Learned: Mixing Relay Technologies in DCB Schemes.
- Current sensing elements used to determine if circuit breakers have opened when called upon to trip may be subjected to repeated pickup and dropout if loading levels fluctuate around the setpoint. While that is not a problem for logic registers internal to a given electronic or digital relay, it can be a problem when the output needs to be routed to a separate device via an auxiliary relay. The auxiliary relay may be subjected to chattering that can result in mechanical damage, including tack welding of its contacts.
- Multifunction microprocessor relays offer a variety of protective elements and schemes. From a protection perspective, it is tempting to employ additional elements to achieve more sensitive fault detection and perhaps faster clearing times beyond what is required. These additional elements, however, also are candidates for misoperation, so that risk must be weighed when considering whether or not to deploy them. Furthermore, they add to the testing required during commissioning, periodic testing, and troubleshooting following an event.

- Failure to recognize that back-up directional overcurrent elements on a PAR were armed to trip as omnidirectional elements despite the absence of a polarizing voltage source highlights the need for thorough oversight, peer reviews, and simulation testing of protection schemes during the design and commissioning stages of new or upgraded protective relaying installations.
- Aux CTs permit compensation of differential relaying to remove sources of imbalance. While this is desirable conceptually, practically it introduces complexity to the overall CT secondary wiring circuits while also adding a component, the aux CT, which is subject to failure itself that can impact the entire differential relaying scheme. Wherever possible, it is preferable to remove the aux CTs altogether and opt for desensitizing the differential relay setpoints to account for known imbalances, provided all faults can still be adequately detected.[2]

  The added complexity of the AC circuits of the protective relays due to the use of aux CTs increases the opportunities for human error in the design, installation, and testing of these circuits. This includes considerations regarding burden calculations, saturation, polarity, and neutral/ground connections as well as the physical requirements for mounting the aux CTs and the routing of control cables to and from them.

The impedance of the return paths for ground fault currents can vary where steel pipe-type transmission cables are used in underground and submarine installations. Magnetic saturation of the steel changes both the resistance and the reactance of the return path to varying degrees, depending on the level of fault current with the resistance changing significantly more than the reactance. While this phenomenon was accounted for in the design of the relaying scheme and its applied settings, the event proved that a multiple fault scenario beyond the design basis can result in dynamic excursions in the zero sequence impedance exceeding expected values. This should be considered when applying stepped distance relaying to protect steel pipe-type cables. The overall scheme was modified so that the Zone 1 elements of the stepped distance relaying that were originally providing continuously armed back-up protection to the line differential relaying were placed on standby to be armed only when the communications needed by the line differential relaying are unavailable. This approach permits the stand-alone distance relaying that doesn't require communications to still provide back-up protection while significantly reducing its exposure to misoperation. It eliminates a potential source of misoperation during the preponderance of time when communications for line differential relaying are available and functioning normally.

NERC's goal with publishing lessons learned is to provide industry with technical and understandable information that assists them with maintaining the reliability of the bulk power system. NERC is asking entities who have taken action on this lesson learned to respond to the short survey provided in the link below.

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[2] There might be a question in cases where inverter based resources have displaced synchronous machines and fault duties are low. Note the phrase "provided all faults can still be adequately detected." That implies that sufficient fault current is still available from sources on the system through transmission ties into the differential relay's zone of protection. Where inverter based resources are predominant to the point that sufficient fault current is not available to the differential zone, the stipulation in that key phrase is not satisfied. In that case, alternative methods of detecting and clearing faults will have to be in place and in service.

For more Information please contact:

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