The “Heart” of the Substation – DC Systems

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***Abstract* — The battery bank of the DC system is the heart of the substation as it is used to operate the protection systems within the substation or generating station and provide power to communications equipment. The battery charger maintains the battery bank and is not designed to provide the current required to trip the circuit breakers. Several recent utility events shed light on the criticality of the battery and substation DC system.**

Similar to many other utilities, Avista’s current practices help mitigate the likelihood but are not comprehensive enough to provide adequate “defense in depth” protection for loss of the battery. In 2018, Avista began a detailed review of our battery system practices and possible solutions to prevent the “other part” of the protection system from failures. As an industry, protection engineers often focus on the protective relays reliability while overlooking the battery system. However, we should make the DC system a key consideration.

This paper discusses several battery-related events and what did or could have happened. The paper also discusses the Human Performance Improvements (HPI) actions that Avista has taken to improve our DC systems.

I. BACKGROUND & INTRODUCTION

The NERC Glossary of Terms [1] defines a Protection System as:

- Protective relays which respond to electrical quantities
- Communications systems necessary for correct operation of protective functions
- Voltage and current sensing devices providing inputs to protective relays
- Station dc supply associated with protective functions (including station batteries, battery chargers, and non-battery-based dc supply), and
- Control circuitry associated with protective functions through the trip coil(s) of the circuit breakers or other interrupting devices.

Protection engineers often focus solely on the protective relay, when considering the reliability of the Protection System. However, the aforementioned NERC glossary of terms remind us of all the components involved in a protection system to provide optimal, reliable protection. The battery bank of the substation DC system is the heart of the substation as it is used to operate the protection systems within the substation or generating station and provides power to communications equipment. The battery charger maintains the battery bank and is not designed to provide the current required to trip the circuit breakers. Several recent utility events shed light on the criticality of the battery and substation DC system.

Thinking of a substation as human anatomy allows us to see the protective relays and remote terminal units (RTUs) as the brain. The circuit breaker can be compared to the human hand that takes direction from the brain. The control circuits are similar to the nervous system. At the center is the heart or the DC system/battery and without it no other portions can work.

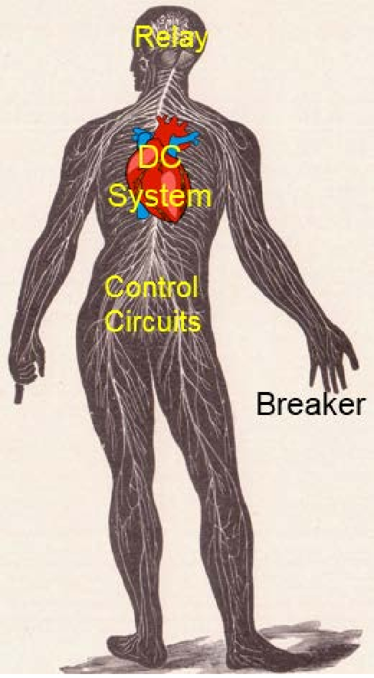


Figure 1 – Substation to Human Anatomy

In 2019, Avista’s Engineering was asked to review a neighboring utilities substation fire. Avista’s leadership was concerned that a battery failure could lead to similar results at an Avista substation. It was decided that a cross-disciplinary team would be tasked with evaluating the events and make recommendations.

One of the questions that might be asked is could this happen elsewhere? It has – in a way – recently happened to Avista but we were fortunate to catch it prior to any damage to capital equipment.

The battery charger is not designed to supply adequate DC current or voltage during a system fault condition [2]. The battery is the source for all DC power under any abnormal condition. Without the battery, essentially all protection equipment is non-functional during any system fault, and there is no DC source to actually trip or operate circuit breakers. The station is operating as a “locked bus” or “solid bus” under these conditions.

The following events are all instances of the loss of the battery through human error or vandalism.

II. EVENT DISCUSSIONS

A. EVENT 1 – OPEN BATTERY MAINTENANCE SWITCH

In 2017, an electrical fault occurred in a substation that resulted in damage estimated at between $4.5M and $7.5M [4].

Leading up to the event, the battery transfer switch, shown in Figure 2 below, was switched to a temporary battery trailer while maintenance was performed on the station battery. However, once the work was completed and the trailer removed, the transfer switched was not returned to its normal operating position, which left the battery disconnected from the DC system and only the battery charger providing DC power. The position of the battery transfer switch was not monitored or addressed in any procedures or inspections and the loss of DC monitor did not alarm because the battery charger provided sufficient DC to satisfy the demand.

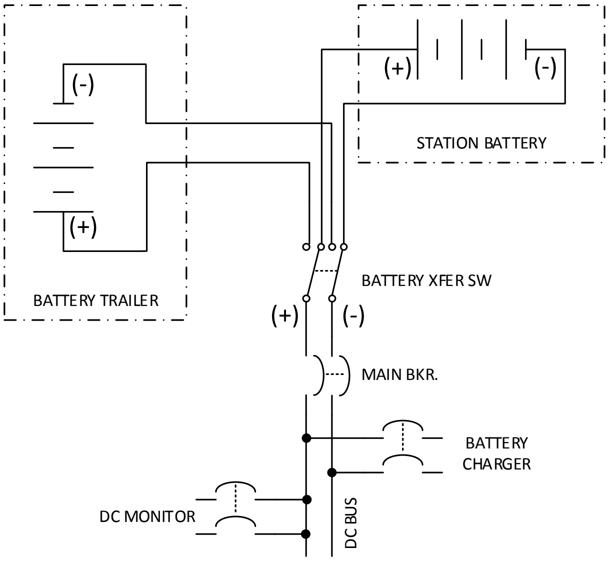


Figure 2 - DC System for Event 1

Although there was insufficient evidence to pinpoint the source of the triggering event, the fault, it was most likely a routine and expected type of fault that was within the design basis of the protection systems. However, contrary to the design of the substation, the fault was not cleared by the redundant fault-interrupt devices (a breaker backed up by a circuit switcher) designed to terminate this type of event. The distribution fault initiated approximately 1750 feet from the substation and the feeder breaker protection operated correctly initially by tripping the breaker and then reclosed as expected. At this point, the fault persisted but the breaker failed to re-open/trip due to the loss of the battery. The 115kV circuit switcher also failed to open as backup protection due to the DC failure. The fault evolved into the substation and eventually propagated into the 115kV section. When the fault evolved into the 115kV section, the remote transmission substations protection schemes operated correctly to clear the fault. The total time of the fault was estimated at more than 3 minutes and resulted in flames and explosions, as witnessed by the utility personnel arriving onsite. Local news reported that the electrical arc and fire were visible throughout the area.

B. EVENT 2 – SUBSTATION THEFT

In 2018, multiple alarms were received in the Control Center from an Avista substation, shown in Figure 3, in the early morning. Responding personnel quickly discovered that the substation fence had been cut near the panel house battery room, and the battery room padlock had been cut. The heavy copper cable between the battery and the panel house had been removed [2]. Efforts were made to quickly repair the damage and return the station to normal. The cutting of the copper cable effectively was the same as the above Event 1 battery transfer switch being mis-positioned which left the battery disconnected from the DC system and only the battery charger providing DC power.

The subsequent day, multiple alarms were again received from the same substation. As with the previous day, the heavy copper cable had been cut, and this time the copper cable was also removed from the panel house to the battery room, and jumpers on the battery. In both cases, the local law enforcement was notified.

During both events, the lack of the battery at the substation resulted in all protective and communications equipment being powered from the battery charger through station service supplied by the 230/115 #1 autotransformer. The supply was subject to all voltage disturbances which would occur during a fault, which severely compromised the integrity of the protection systems. The additional load of breaker tripping generally exceeds the capabilities of the battery charger. The battery charger carries normal DC load under normal conditions. The battery carries load and supplies additional current during system fault conditions, breaker tripping, and provides a backup in the event of a station service failure. Without the battery, essentially all protection equipment is non-functional during any system fault, and there is no DC source to actually trip or operate circuit breakers. The station is operating as a “locked bus” or “solid bus” under these conditions.

As a “locked bus”, with all protection equipment compromised under fault conditions, any fault which occurs on the 230 kV, 115 kV, or 13 kV lines terminating at the substation shown in Figure 3, must be cleared remotely and thus severely compromises the Bulk Power System (BPS). Any fault requiring clearing from the substation on the BPS would not be isolated and cleared by normal protective equipment function. Such a failure, based on system operating conditions at the time, would have resulted in widespread outages and generating plants tripping throughout northeastern Washington, northern Idaho and Montana. Although there is no industry definition for the term “near miss,” this event characterizes a near miss because the BPS was one contingency away from a widespread cascading outage during both battery failures [2].

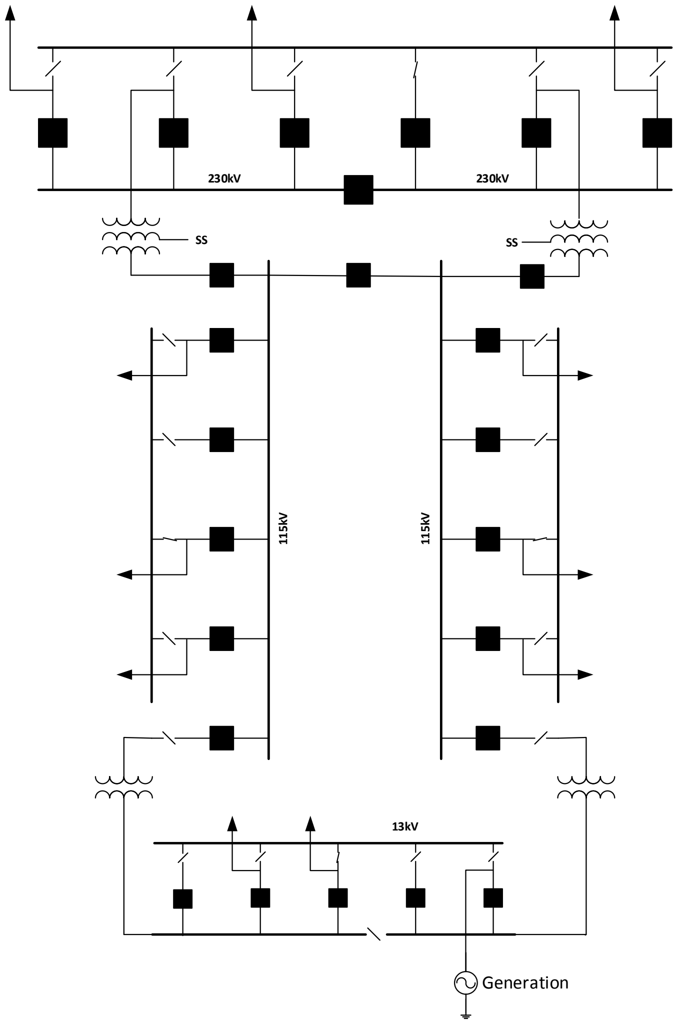


Figure 3 – Avista Substation

A fault would be the next single contingency event, which is considered a likely event. A three-phase or phase-to-phase fault is the most severe type of fault, and requires impedance relaying to detect and clear a fault. A single-line-to-ground fault relies on overcurrent to detect and clear a fault depending on the location in the system. A fault would result in tripping every line feeding the substation on the 230 kV and 115 kV system if the remote substations impedance relays were able to detect the fault. Figure 4 shows that the remote substations RS_2 and RS_3 Zone 2 elements will not reach a remote fault at RS_1 since industry practice is to set these typically at 120-130 percent.

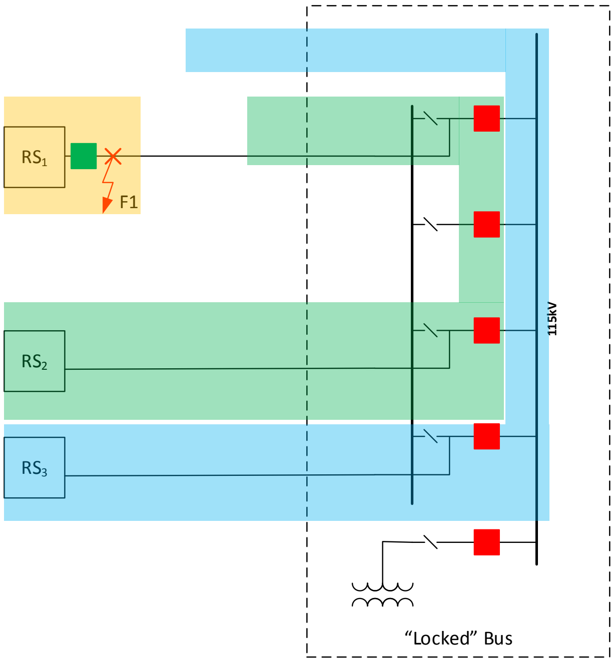
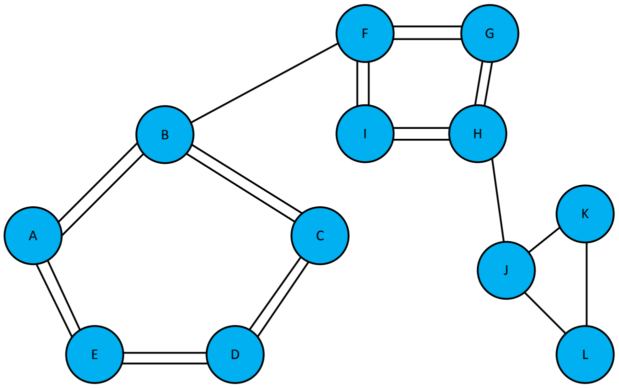


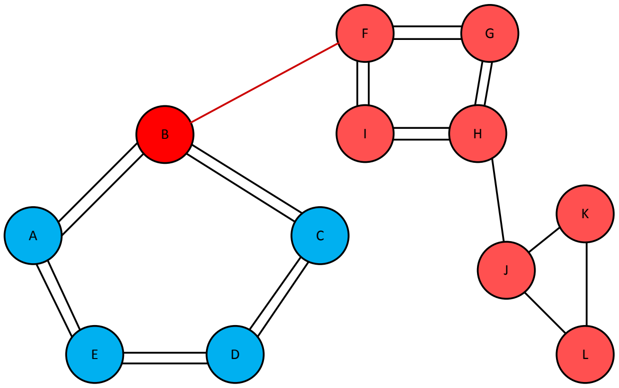
Figure 4 – Reach through "Locked" Bus

A fault occurring on the 13 kV feeders would likely not clear at all. All three possibilities would likely result in the failure of both 230/115kV autotransformers (cost of approximately $2.8M/transformer). Additionally [2] points to the likely loss of approximately 2780MW of generation minus load loss due to widespread out-of-step generation. For reference, the Western Interconnection Resource Loss Protection Criteria (RLPC) is determined using a double Palo Verde nuclear plant outage, where the loss of the generation minus load loss credit is 2624 MW. This supply loss produces a frequency drop of approximately -0.3 Hz [3]. Therefore, in our scenario, a loss of 2780 MW would likely result in a frequency decline exceeding -0.3 Hz (59.7 Hz) [2].

It is obvious that protection relays at the substation were impacted, but as protection engineers, we need to consider the effects to the complete Protection System. In this case, communications were also interrupted to multiple sites that relied on the substation communication equipment due to the failures caused by the theft as shown in Figure 5. The affected communication racks were supplied by 125VDC to 48VDC converters.



(a) System Normal



(b) System During Event

Figure 5 – Avista Communications Circuits

C. EVENT 3 –CREW ERROR

In early 2020, substation personnel were tasked with returning a substation control house battery to service that had been removed from operation for testing. Restoring the circuit to its normal configuration required the crew to make parallel between the control house battery (currently out-of-service) and the trailer battery (utilized to temporarily supply DC power) prior to disconnecting the trailer battery, in order to retain continuity of the DC circuit.

After a walk down was performed, the team notified the Control Center of their work activities. They proceeded to place the outside battery trailer disconnect switch in the OPEN position and then turned off both battery chargers in the control house resulting in a total loss of DC to station equipment.

The crew failed to make parallel between the two sets of batteries prior to removing the temporary battery from service. They had the mindset that they could "blink" the DC source for a short period of time while returning the control house battery to service. The loss of DC source lasted 70 seconds.

III. HUMAN PERFORMANCE IMPROVEMENT

A. WHAT IS HUMAN PERFORMANCE?

Human performance improvement (HPI) as addressed in this paper is not a program per se, such as Six Sigma, Total Quality Management, and the like. Rather, it is a set of concepts and principles associated with a performance model that illustrates the organizational context of human performance. The model contends that human performance is a system that comprises a network of elements that work together to produce repeatable outcomes. The system encompasses organizational factors, job-site conditions, individual behavior, and results. The system approach puts new perspective on human error: it is not a cause of failure, alone, but rather the effect or symptom of deeper trouble in the system. Human error is not random; it is systematically connected to features of people's tools, the tasks they perform, and the operating environment in which they work [5].

The ultimate goals of human performance are to 1) anticipate, prevent, catch, and recover from active errors and 2) identify and eliminate latent organizational weaknesses. If opportunities to err are not methodically identified, preventable errors will not be eliminated. Even if opportunities to err are systematically identified and prevented, people may still err in unanticipated and creative ways. [5].

B. MANAGING CONTROLS

Events, such as those discussed above, involve breaches in controls or safeguards. It is essential therefore that management take an aggressive approach to ensure controls function as intended. The top priority then should be to identify, assess, and eliminate likeliness of an event. For the purposes of this paper, five (5) general types of controls are reviewed in brief.

- Hazard Elimination During Design - Organizations evaluate operations, procedures and facilities to identify workplace hazards. Management implements a hazard prevention and elimination process.
- Engineered Defenses - These provide the facility with the physical ability to protect from errors. To optimize this set of controls, equipment must be reliable and kept in a configuration that is resistant to simple human error and allows systems and components to perform their intended functions when required.
- Administrative Defenses - Policies, procedures, training, work practices processes, administrative controls and expectations direct people's activities so that they are predictable and safe and limit their exposure to hazards, especially for work performed in and on the facility.
- Cultural Norms - These are the assumptions, values, beliefs, and attitudes, and related leadership practices that encourage either high standards of performance

or mediocrity, open or closed communication, or high or low standards of performance.

- Oversight Defenses - Accountability for personnel and facility safety, for security, and for ethical behavior in all facets of facility operations, maintenance, and support activities is achieved by a kind of “social contract” entered into willingly by workers and management where a “just culture” prevails [5].

The solution simply put is a culmination of these defenses and not any one control can prevent a breach. The best solution is a “defense in depth” approach. Avista already has “defense in depth” practices associated with the risk. During the analysis and discussions with the team of the events, the following practices were identified as measures that Avista takes that help mitigate the risk.

- Use of SCADA to Battery Trailer - When Avista installs the battery trailer for battery testing (disconnecting the substation battery), the trailer SCADA system is checked-out with System Operations so that the status of the battery trailer service in the substation can be monitored 24/7. System Operations will receive alarms in the event that there are battery issues.
- Three (3) – Way Communication - Avista Generation & Production / Substation Support (GPSS) craftsman use three-way communications with the System Operators when doing maintenance, testing, repair, or replacement of batteries.
- SCADA DC/Battery Charger Alarms - Avista substations with SCADA include battery charger alarms and low-voltage (27) alarms at older substations. The majority of the alarming is related to the battery charger status and voltage at the protective relays. Though helpful these do not give indication of a battery being disconnected as long as the battery charger(s) are carrying the load.

The following recommendations were made to improve the defense in depth strategy. The recommendations were presented to management and ultimately accepted.

- Battery Commissioning Process - Avista presently did not have a formal battery commissioning practice. The team recommend developing a formal battery commissioning process that can be used among all groups, i.e. Generation, Communications, and Substations Engineering to ensure successful implementation.
- Battery Disconnect Status in SCADA/EMS - There are several installations in both generation and substations that have existing disconnect switches. We recommend adding the disconnect position into SCADA/EMS (even if manually changed) and, when active, adding it to the exception list, which is to be discussed by the System Operators at shift turn-over.
- Battery System Subject Matter Experts (BSME) - The SME’s are responsible for reviewing proposed changes to battery system designs from all points of view to ensure that latent conditions are not inadvertently designed into the critical battery system. The team consist of SME’s from Substations, Generation, Communications, System Protection and field crews.

IV. CONCLUSION

Over the last several years, utilities have seen an increase in substation break-ins and loss of critical systems. Even without the break-ins, utilities must reevaluate present practices to ensure that critical systems do not have latent conditions that can lead to the system being unavailable when needed. The events discussed in the paper provide good examples of the criticality of battery systems.

Numerous recommendations are being made to improve Avista’s battery system and practices to reduce the likelihood of the loss of a substation due to the loss of the battery. Key observations are:

- Chain link fencing is vulnerable to common hand tools.
- Padlocks do not provide security against common bolt cutters.
- "Blinking" of DC power is never permissible. Control house DC source must always be present and is required for relay protection schemes to operate as designed.
- DC power supplied by battery charger(s) is not enough (or sufficient) to operate substation equipment.
- It is common for there to be a “Lack of understanding of DC" when utilities don’t prepare their personnel enough. It is recommended that your utility review and update training material to ensure proper information transfer. Ensure that all battery/DC system configurations used by the utility are covered.
- Use ‘tags’ installed on switches and temporary leads when creating an abnormal condition informing others of the abnormal condition and who to contact before changes are made.
- Use a checklist during making and breaking parallel with DC sources.
- Add a check of any single-point of failures in the DC supply to the monthly substation inspection checklist or monitor the status.

V. References

[1] North American Electric Reliability Corporation (NERC), "Glossary of Terms Used in NERC Reliability Standards," 2020. [Online]. Available: https://www.nerc.com/files/glossary_of_terms.pdf. [Accessed 23 07 2020].

[2] S. T. O. E. Rich Hydzik, "2018-06-27 and 06-28 AVA Beacon Battery Equipment Theft," Avista Utilities, Spokane, 2018.

[3] North American Electric Reliability Corporation (NERC) - IRPTF, "Resource Loss Protection Criteria Assessment," NERC, Atlanta, 2018.

[4] PUD, "Substation 2017 Uncontrolled Fault Event," PUD, WA, 2017.

[5] U.S. Department of Energy, "Human Performance Improvement Handbook, Volume 1: Concepts and Principles (DOE-HDBK-1028-2009)," U.S. Department of Energy, 2009.

VI. Biography

Kevin Damron received his BS in electrical engineering from the University of Kentucky in 2001, a ‘Power Systems Protection and Relaying’ certificate from the University of Idaho in 2009, and a Masters of Engineering - Transmission and Distribution Engineering from Gonzaga University in 2020. In 2002, he joined Schweitzer Engineering Laboratories, Inc. as a power engineer in the research and development division. After leaving SEL, Kevin worked at a consulting firm providing engineering and consulting services before joining Avista in 2010 in the System Protection group. Kevin has broad experience in the field of power system operations, maintenance, and protection and has authored/coauthored several papers on protective relaying. Kevin is a registered professional engineer in Washington State, an adjunct professor at Gonzaga University, and is an IEEE Senior Member.

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