A Bus Cleared and a Hidden Breaker Insulation Failure Revealed

Robert Roman and Kevin Damron
Avista Utilities

Emma Clawson
Schweitzer Engineering Laboratories, Inc.

Revised edition released June 2025

Previously presented at the
78th Annual Georgia Tech Protective Relaying Conference, May 2025,
and 78th Annual Conference for Protective Relay Engineers at Texas A&M, March 2025

Originally presented at the
51st Annual Western Protective Relay Conference, October 2024

A Bus Cleared and a Hidden Breaker Insulation Failure Revealed

Robert Roman and Kevin Damron, *Avista Utilities*
Emma Clawson, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—On June 27th, 2023, lightning struck a transmission line about one mile from a substation. Shortly after the first lightning strike, the high-impedance bus differential relay cleared the bus at the substation even though there was no apparent fault on the bus. About half an hour after these two events, the percentage-restrained bus differential relay attempted to trip the bus again, even though the bus was still de-energized from the initial events.**

In this paper, the protection engineers unravel the mystery of what cleared the bus initially and why. It also explains what caused the percentage-restrained bus differential relay to subsequently attempt to trip the bus when it was already de-energized.

I. Introduction

Lightning struck a transmission line about one mile from Substation (Sub) A on June 27th, 2023. The bus at Sub A was cleared almost immediately after the lightning strike without any clear evidence as to why. About half an hour after this, the percentage-restrained bus differential relay asserted its trip output, even though the bus was still de-energized. Technicians arrived at the substation, did not find any evidence of a bus fault, and proceeded to successfully re-energize the bus.

Was there a fault on the bus? What tripped the bus the first time? The initial assumption was that lightning had struck both the transmission line and the bus at the same time, but was that assumption correct? Why did the percentage-restrained bus differential relay trip the bus when it was de-energized? This paper unravels the mystery of what initially cleared the bus and why. It also explains why the percentage-restrained bus differential relay tried to trip the de-energized bus again.

NERC PRC-004-6 requires Transmission Owners to review the Bulk Electric System (BES) operations to ensure the Protection System operates correctly, but it does not specify to what level the review should be performed. Modern microprocessor relays provide a significant amount of information for protection engineers to use in their analysis, and by digging into the details, they can uncover important information if they take adequate time to analyze the events.

The following sections discuss the principles of high-impedance and percentage-restrained bus differential relays, which were both involved in the event, and the event analysis to reveal how deeper digging needs to be done when the full details of an operation are unknown. The paper also covers the basics of how lightning can affect the transmission system and how it affected the equipment during this event.

II. High-Impedance and Percentage-Restrained Bus Differential Principles

A. High-Impedance Bus Differential General Principles

High-impedance bus protective relays parallel the output of all current transformers (CTs) from the zone of protection and connect them to a common point, as shown in Fig. 1. As the name implies, the relay provides a high impedance to the flow of current. It is important to match the CT ratios, polarity, and the CT accuracy classes to minimize the difference in CT performance that could lead to false differential current.

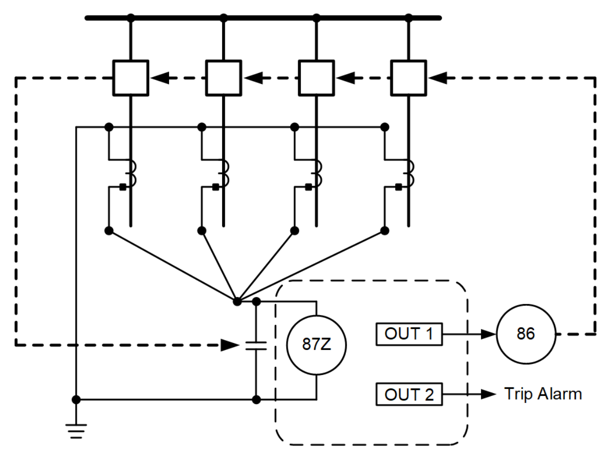


Fig. 1. Four (n) paralleled CTs connected to a high-impedance bus differential relay [1].

Under normal load conditions, the sum of the currents from the CTs is zero so that no current flows through the high-impedance element of the relay, as shown in Fig. 2. This behavior is similar for an external fault without CT saturation, because the sum of the fault current through each of the CTs on the protected bus is still zero.

Fig. 2 shows a current source, CT A, which represents the sum of all CT secondary currents except for one. The current source shown as CT B represents the current flowing through the remaining CT in the circuit of n CTs.

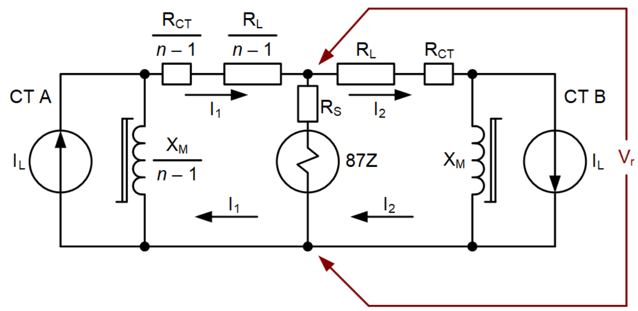


Fig. 2. Equivalent CT circuit showing balanced current in parallel CTs [1].

For an external fault with CT saturation, the magnetizing impedance of the saturated CT becomes very small, and almost all the current flows through the magnetizing impedance of the CT rather than through the CT secondary leads to the relay. The saturated CT circuit becomes a current path represented by the internal CT resistance, R_{CT} [1]. The worst-case voltage, V_r, developed across the relay is the voltage drop across the CT lead, R_L, and internal resistance, R_{CT}, for a worst-case maximum external fault condition. Fig. 3 shows CT B saturated for an external fault with CT A representing the other *n* – 1 CTs that are not saturated. The remaining *n* – 1 CTs with sources are feeding the fault. The voltage threshold setting in the relay is set above this worst-case V_r by a margin specified by the utility's standard to ensure the relay settings are secure against misoperation.

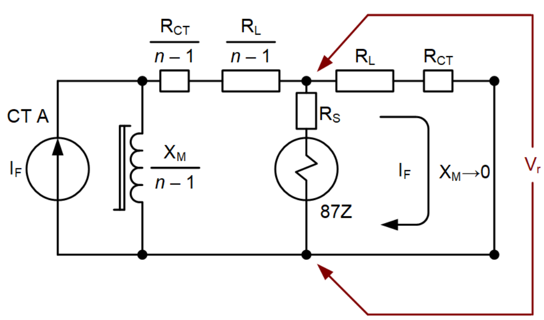


Fig. 3. Equivalent CT circuit showing the effects of CT saturation on the faulted circuit for an external bus fault [1].

For an internal fault, all the primary current sources contribute to the total bus fault current [1]. Since the sum of the CT secondary currents is no longer zero, the total secondary current initially flows through the high impedance of the relay, creating a very high voltage, as shown in Fig. 4. This high voltage quickly causes the relay's metal-oxide varistor (MOV) to conduct, limiting the voltage across the relay, and drives the CTs into saturation. The voltage developed across the relay is much greater than the setting threshold of the relay, causing it to trip.

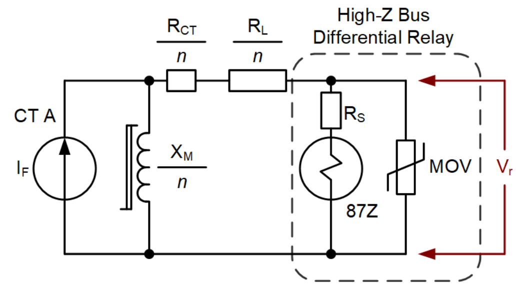


Fig. 4. Equivalent CT circuit for *n* CTs driving current into the high-impedance relay for an internal fault [1].

B. Percentage-Restrained Bus Differential General Principles

Percentage-restrained bus differential relay current inputs present a low impedance to the flow of current in the CT secondary [1]. A percentage-restrained bus differential relay typically has a set of current inputs for each phase of each CT connected in the scheme, as shown in Fig. 5. The relay compensates for the different secondary currents by using settings to normalize each current to a common per-unit base.

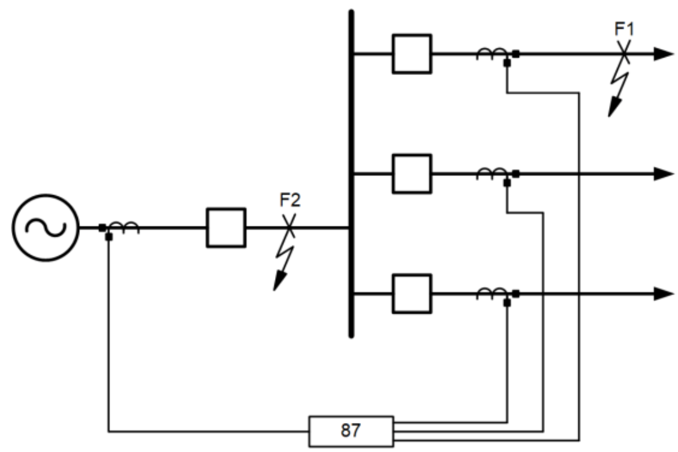


Fig. 5. Percentage-restrained bus differential scheme showing an external fault F1 and an internal fault F2 [1].

The percentage-restrained bus relay vectorially sums the normalized currents from all CT inputs of the protected zone to detect a differential operate current, I_{OP}. To account for any differences in CT performance, the relay also arithmetically sums the current magnitudes to create a restraint current, I_{RT}. The differential current I_{OP} is compared to I_{RT}. The relay will operate when the I_{OP} current exceeds a minimum threshold and a percentage of I_{RT} [1]. As shown in Fig. 6, for normal load conditions the operate current is practically zero and the restraint current is proportional to the load current, while for an internal fault, both operate and restraint currents are high. Note that there is a bus differential zone for each phase, so I_{OP} and I_{RT} are calculated per phase.

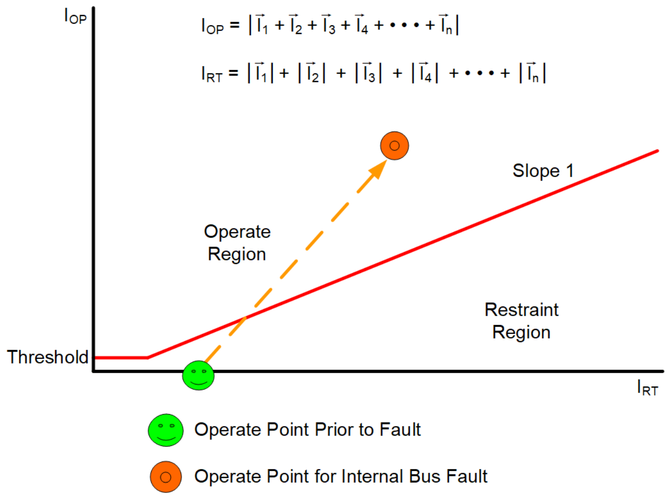


Fig. 6. Percentage current differential characteristic of a percentage-restrained bus differential relay with and without an internal bus fault [1].

Modern percentage-restrained bus relays employ a variety of techniques to ensure that the relay properly distinguishes between internal faults and external faults, especially during CT saturation and nonfault transients [1]. The relay uses the first few milliseconds of rising fault current before CT saturation occurs to make an internal or external fault determination. In simple terms, if the relay detects a rise in restraint current without a rise in operate current, it goes into a high-security operating mode, the fault is declared external, and the relay does not operate. If the relay detects a rise in restraint current along with a corresponding rise in operate current, then the fault is declared internal and the relay can operate.

C. Differences Between High-Impedance and Percentage-Restrained Differential Operation in the Context of This Event

In the context of the events discussed in this paper, there are important differences between the high-impedance and percentage-restrained bus differential schemes. The high-impedance bus differential relay measures voltage pulses that are a function of the CT class and MOV characteristic. The relay proceeds to calculate the voltage magnitude from the filtered voltage pulses, which is then compared to the pickup setting [2]. Once the bus lockout relay (86B LOR) rolls, the high-impedance bus differential relay inputs are shorted to protect the MOV from thermal damage. See Fig. 1 for an illustration of the 86B LOR.

The percentage-restrained bus differential relay measures the current from each CT individually, filters each current, and then calculates the operating and restraint currents for each phase from the filtered currents. This relay operates on the principle of continuously comparing the operate and restraint currents along with external fault supervisory elements to make certain that the relay issues a trip only for internal faults [1].

III. Lightning Impulse Effects on the System

Direct lightning strikes are a major source of flashovers based on the line location and tower structure configuration. High-voltage “traveling waves injected onto phase conductors by tower flashovers or by [shield wire] failures can travel for long distances to enter substations and present severe challenges to transformers, circuit breakers, and other components” [3]. Utilities perform insulation coordination to minimize the interruptions and damage due to abnormal voltages. However, all means of insulation coordination come with tradeoffs and costs, so utilities must weigh risk versus cost when implementing solutions.

Fig. 7 shows the total lightning density across the utility’s service territory for one year (2023). A review of the historical data [4] shows the total lightning density to have been lower than shown in Fig. 7. Shield wires and surge arresters were not included in the original design of the substation based on the low risk of lightning in 1978, when the substation was constructed.

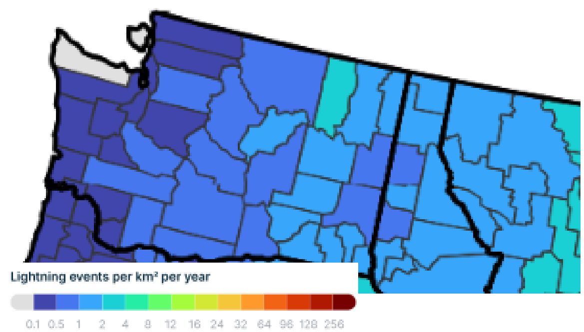


Fig. 7. Total lightning density for the utility’s service territory [4].

IV. Event Analysis

A. Background and Sequence of Events

Sub A is a 230 kV substation with five 230 kV breakers, as shown in Fig. 8. The breakers relevant in the following events are Breaker (Bkr) 2 and Bkr 3. The relays protecting the Sub A–Sub B line on the Sub A end of the line were modern line relays, and the relays protecting the Sub A–Sub C line at the Sub A end of the line were legacy line relays. The Sub A bus protective relays were a modern high-impedance bus differential relay and a modern percentage-restrained bus differential relay, referred to as 87B1 and 87B2, respectively.

The initial information received from the system operators was that the Sub A–Sub B line (Bkr 3 and Bkr 7) and the Sub A bus (Bkr 1, Bkr 2, Bkr 3, Bkr 4, and Bkr 5) had tripped at the same time. The initial thought was that lightning had struck the Sub A–Sub B line and the Sub A bus at the same time. The technicians arrived at the substation, saw no visible damage from the fault, and therefore, proceeded to re-energize the Sub A bus and the Sub A–Sub B line. There was no indication or idea that any of the breakers might have been compromised or that a second fault had occurred while the Sub A bus had been open.

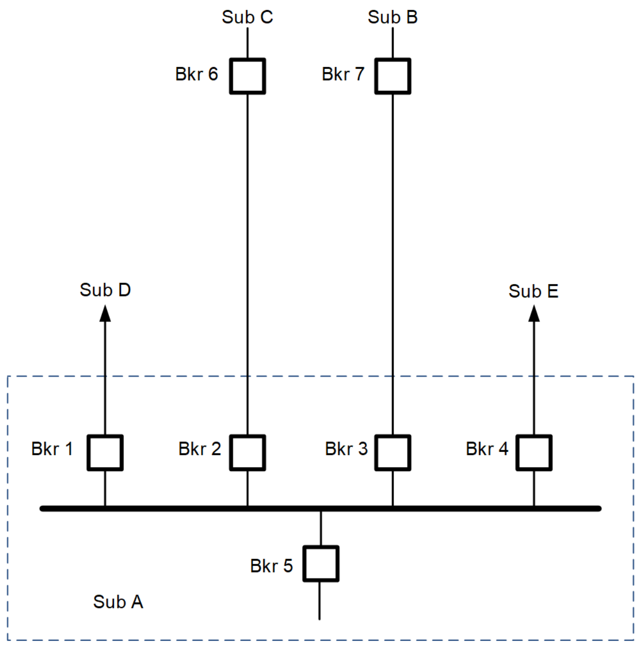


Fig. 8. Sub A configuration.

Table I summarizes the sequence of events, which are discussed in detail in the following sections. The times throughout the paper have been adjusted to the relay's time zone.

TABLE I
SEQUENCE OF EVENTS

Time	Event
16:37:00.5165	Sub A–Sub B line BG fault occurs
16:37:00.5270	Sub A–Sub B line relays trip
16:37:00.5606	Sub A–Sub B line relays Bkr 3 52A deasserts
16:37:00.9546*	87B1 trips Sub A bus
16:37:00.9850	87B2 Bkr 4 52A deasserts
16:37:00.9860	87B2 Bkr 1 52A deasserts
16:37:00.9864	87B2 Bkr 5 52A deasserts
16:37:00.9874	87B2 Bkr 2 52A deasserts
16:37:01.6553	Sub B Bkr 7 recloses
17:05:21.2273	87B2 attempts to trip Sub A bus
17:05:21	Sub C Bkr 6 trips
17:05:22	Sub C Bkr 6 recloses

* The exact time of the 87B1 trip is unknown since it was not receiving the Inter-Range Instrumentation Group time code format b (IRIG-B) time signal. The time recorded in this table was approximated by aligning the 87B1 relay event report with the 87B2 relay event report and taking the time of the 87B1 relay trip from the 87B2 relay.

B. *Sub A–Sub B Line Protection Analysis—Initial Fault*

At 16:37:00 a B-phase-to-ground fault occurred on the Sub A–Sub B transmission line. Both modern line relays at Sub A detected the fault and tripped on their Zone 1 distance element, Z1G. Bkr 3 opened within about two and a quarter cycles, opening the line from the Sub A end. Both relays showed the 52A contact from the breaker deasserting, which also indicated that the breaker opened. Fig. 9 shows the current and binary values from the modern line relays for the fault. The currents for both relays are nearly identical so only one set of currents is shown. The relay estimated the fault location to be 0.73 miles from the substation. This is very close to Sub A since the total line length was approximately 70 miles. The other end of the line at Sub B also tripped quickly due to the permissive overreaching transfer trip scheme and opened the remote breaker.

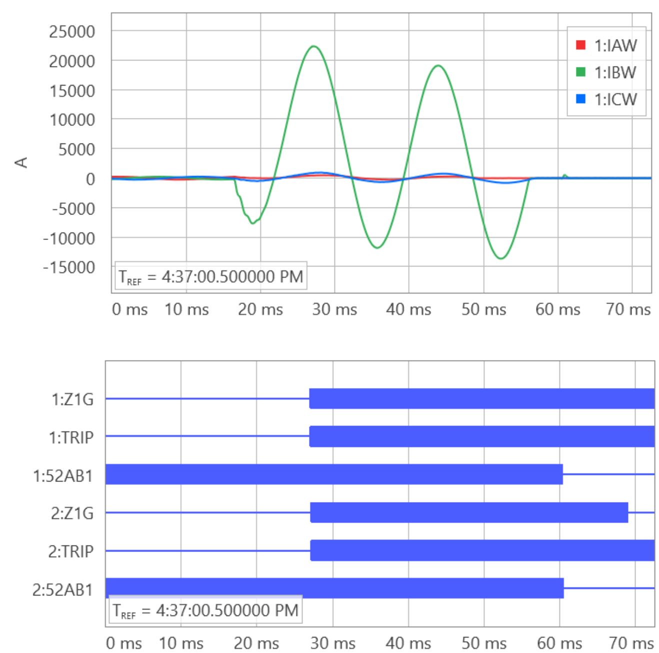


Fig. 9. Initial fault detected by the modern line relays protecting the Sub A–Sub B line.

C. *Sub A Bus Protection Trip*

After the line relays cleared the fault and opened Bkr 3, the Sub A bus was cleared. Initially the system operators thought that the bus and the line cleared at the same time due to the same fault. The event analysis of the 87B2 relay's Sequential Events Recorder (SER) report showed that there was a 434.5 ms time difference between the time that the 52A contacts from Bkr 3 opened from the line relay's trip command and the time that the 52A contacts of the other breakers on the Sub A bus began opening. It was also observed from the 87B2's SER report that the 87B2 relay did not trip the bus. The 87B1 relay tripped the Sub A bus.

Digging deeper into the 87B1 relay's filtered compressed event report files, the engineers observed the voltage signal shown in Fig. 10a. This signal looks similar to an impulse response of the 87B1 half-cycle cosine filter. The impulse response of a half-cycle cosine filter at eight samples per cycle should be four samples long. However, the signal shown in Fig. 10a has five samples. The reason for this signal in the 87B1 relay is discussed later in this section, after the signals shown by the 87B2 relay's COMTRADE files are discussed. The magnitude of this signal rose above the 87B1P setting in the 87B1 relay for one processing interval, causing it to trip, as shown in Fig. 10b and Fig. 10c.

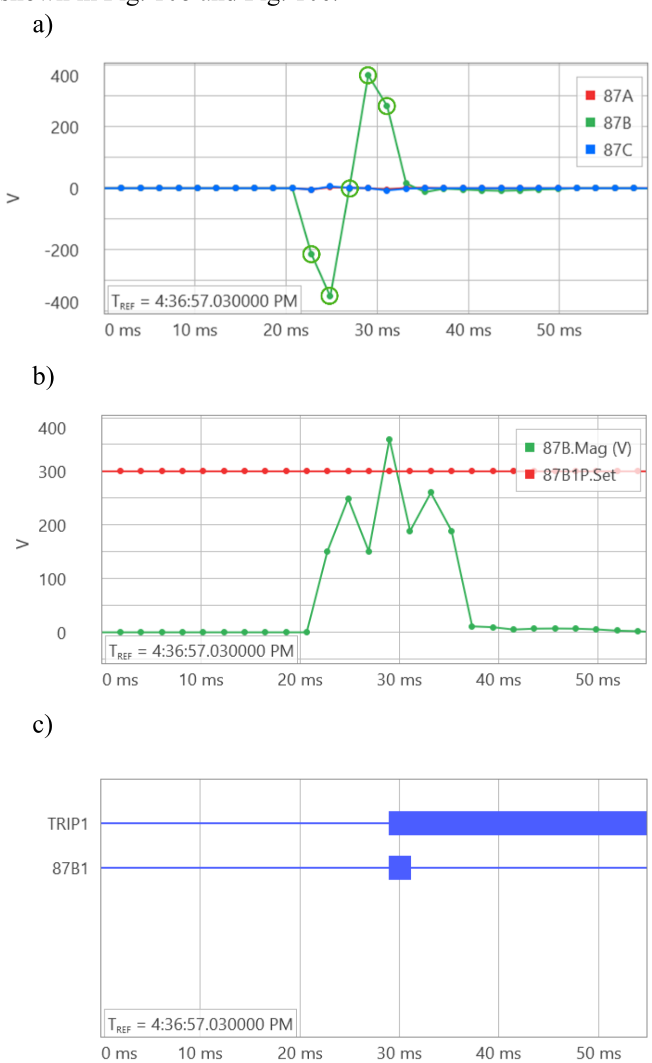


Fig. 10. 87B1 relay tripped the Sub A bus.

The protection engineers proceeded with the event analysis by looking at the 87B2 relay's COMTRADE event. An initial look at the currents and voltages in the 87B2 event showed the voltage at nominal voltage and the current at normal load current values with no sign of a bus fault. A more detailed look revealed that although the currents through Bkr 3 were zero at the beginning of the event, which started after Bkr 3 had opened, the B-phase current had several large, high-frequency transients. These transients were due to lightning strikes on the line, as shown in Fig. 11a. Somehow, Bkr 3 was open but current still flowed through the CT. Current is not supposed to flow through open breakers. This was the first indication that the breaker was damaged, which will be discussed more later.

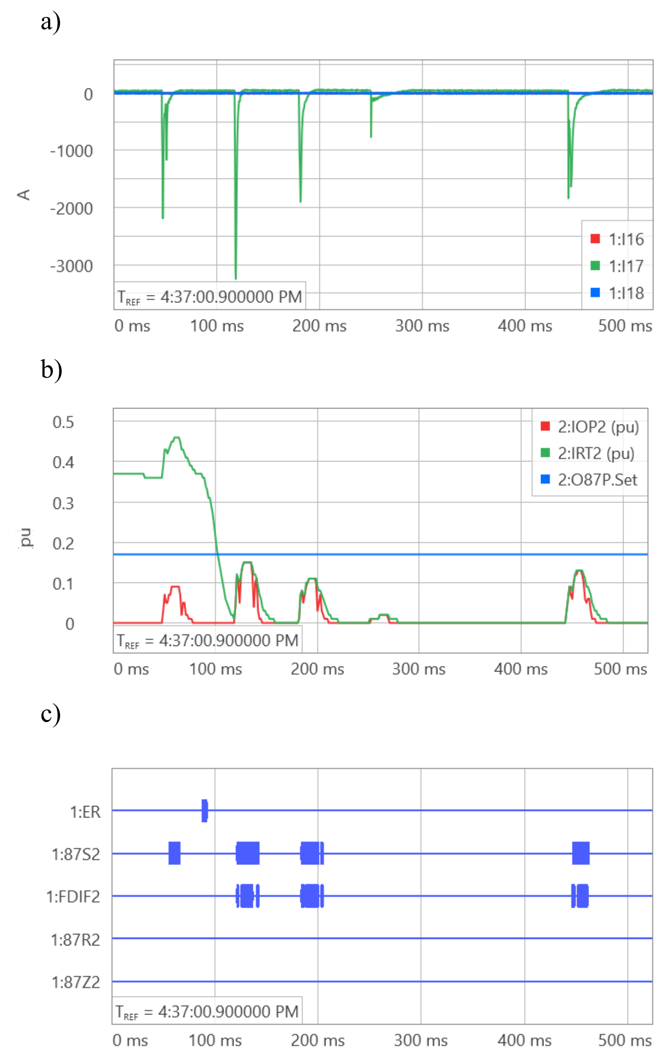


Fig. 11. High-frequency current transients in the 87B2 currents.

Before continuing to analyze the 87B2 relay's response to these high-frequency lightning strikes, recall the signal observed in the 87B1 relay's event report. Fig. 12 shows the first lightning strike from the 87B1 relay's unfiltered voltage, 1:87B, and the 87B2 relay's unfiltered current, 2:I17. The 87B1 relay's event record is a 16-samples-per-cycle (960 Hz when the nominal frequency is 60 Hz) unfiltered event record, and the 87B2 relay's event record is an 8 kHz COMTRADE event record. The 87B1 relay's lower 16-samples-per-cycle sampling rate caught only two data points that had a high value in the unfiltered event report. When these two points passed through the half-cycle cosine filter of the 87B1 relay and were downsampled to eight samples per cycle, the result was the five-point signal shown in Fig. 10a. The 87B1 relay samples data at 16 samples per cycle, but the filtered event reports it records are 8 samples per cycle. This analysis of the relay's filtering explains the nontypical signal seen in the 87B1 relay's event report.

The 87B1 relay only saw the initial lightning flashover in the breaker and not the subsequent ones because as soon as the 87B1 output to the LOR asserted the LOR shorted the inputs to the 87B1 to protect the internal MOV of the relay from thermal damage, as previously discussed.

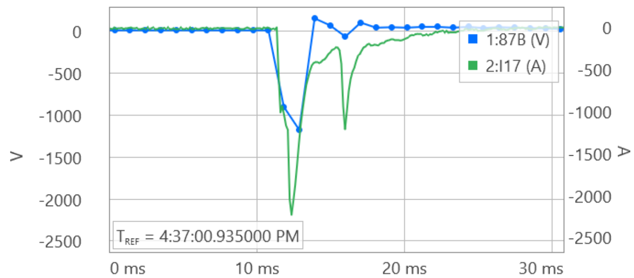


Fig. 12. First lightning strike seen by 87B1 and 87B2 relays.

It is evident from Fig. 11c that the 87S2 binary output, which is the sensitive differential element for the second B-phase zone in the 87B2 relay, picked up and dropped out when lightning struck the line and flashed over in the breaker. The time-delayed output of the sensitive differential element, 87ST2, is mainly used for alarming in the 87B2 for long-time standing imbalances from CT circuit failure. The pickup setting for the 87S2 binary output, S87P, was set to 0.07 per unit (pu) and the pickup delay setting, 87STPU, was set to 300 cycles. Since the operate current for B-phase, IOP2, went above the S87P setting, the sensitive differential element asserted momentarily, but it did not assert the alarm because the operate current was not above the pickup setting for 300 cycles.

The filtered differential element in the 87B2 relay did not assert. This element requires the percentage of operate and restraint current to be above a slope setting and the operate current to also be above a minimum pickup current setting. When the percentage of operate current to restraint current exceeds the slope setting, the FDIF2 binary output asserts, indicating that the filtered differential element picked up. When both conditions are satisfied, as well as other supervisory logic, the 87R2 binary output, which is the B-phase filtered differential element output, will assert. The 87B2 relay was set to trip on the 87Z2 binary output, which is a supervised version of the 87R2 binary output.

Since the magnitude of the operate current due to the first lightning strike was at almost 0.1 pu and the load current caused the restraint current magnitude to be about 0.35 pu, the 87B2 relay did not operate, as shown in Fig. 11b and Fig. 11c. After the 87B1 relay tripped the bus and the load current went to zero, the subsequent lightning strikes caused the operate and restraint current to have about the same magnitude. The FDIF2 binary output asserted for these subsequent lightning strikes because the operate and restraint current percentage was greater than the slope setting. But the 87R2 binary output did not assert for the subsequent lightning strikes because the operate current did not exceed the minimum magnitude check of the O87P setting, which was set to 0.17 pu. The operate and restraint current rose up to 0.15 pu but never reached the 0.17 per-unit setting. Therefore, the 87R2 and 87Z2 binary output did not assert and the 87B2 relay did not trip.

Each of these settings, and the logic in the relay, was intentional. The 87B2 relay is not designed to operate on transient, high-frequency currents that last less than a quarter of a cycle. It is designed to operate on the fundamental frequency of the power system or transients that last longer than a quarter of a cycle.

There was no indication that the current from the lightning strike was seen by the Bkr 3 line relays. No event report was generated after the initial line fault event record and no binary outputs in the SER report indicated that the relay saw the high-frequency current transient. The disturbance detection binary output, 87DD, did assert for a brief period of time, but judging by the time that it asserted, it must have been due to the Sub A bus voltage transients when the bus was cleared by the 87B1 relay.

The CTs for the bus relays are on the line side of the breaker, and the CTs for the line relays are on the bus side of the breaker because the zones of protection for the bus and the line overlap at the breaker. The only way the bus relays' line-side CTs could see high-frequency current transients without the line relays' bus-side CTs seeing any current flow is if the current flowed from the line through the primary of the line-side CTs into the breaker and flashed over to ground through the tank of the breaker, as shown in Fig. 13.

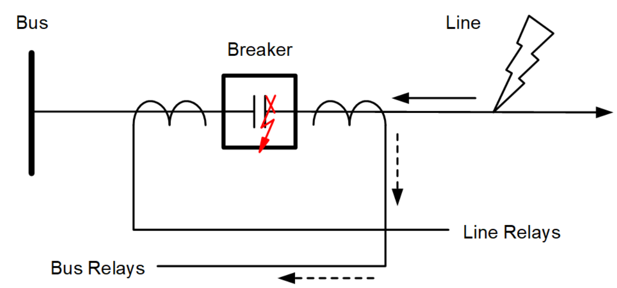


Fig. 13. Internally faulted breaker.

D. *Sub B Successful Reclose*

One second after Sub B opened Bkr 7 to clear the initial fault on the line, Bkr 7 successfully reclosed the Sub B end of the line. The current went from zero to supplying about 42 A of charging current to the line.

It is interesting to note that although Bkr 3 had flashed over due to the lightning strikes, the breaker was able to withstand the nominal voltage of the line when the Sub B end of the line reclosed. The breaker was also able to be closed when the Sub A bus and Sub A–Sub B line were re-energized successfully.

E. *Lightning Report Data for the First Fault*

The protection engineers obtained a lightning report from STRIKEnet that contained the date, time, location, and kA of the lightning strikes within a 15-mile (mi) radius around Sub A from about 12:00 to 17:30. The relevant information from the lightning report is shown in Table II.

TABLE II
LIGHTNING STRIKE DISTANCE FROM THE LINE

Lightning Strike Time	Approximate Distance From Sub A (mi)	Approximate Distance From Line (ft)
16:37:00	0.625	NA*
16:37:00	0.606	341
16:37:00	0.890	156
16:37:00	0.890	65
16:37:00	0.890	40
16:37:00	1.004	0
16:37:00	0.871	176
16:37:00	0.871	NA*
16:37:01	0.890	252
16:37:01	0.890	77

* In these cases, the lightning strike was in a random direction in relation to the substation and was nowhere near the transmission line.

As mentioned previously, the modern line relays on the Sub A–Sub B line reported a distance of 0.73 miles from Sub A for the initial line fault at 16:37:00.5271. The 0.73-mile distance from the substation reported by the relay lines up well with the approximate 0.6- or 0.89-mile distance from the substation provided in the lightning report. About 430 ms later, the 87B2 bus relays saw five other high-frequency current transients from 16:37:00.9463 to 16:37:01.3418, one of which was small and may have been a reflection. The lightning report only provides times in whole seconds, but it does show a total of eight potential lightning strikes that were located within 350 ft of the transmission line from 16:37:00 to 16:37:01. This shows a strong correlation between the data from the lightning report and the relay.

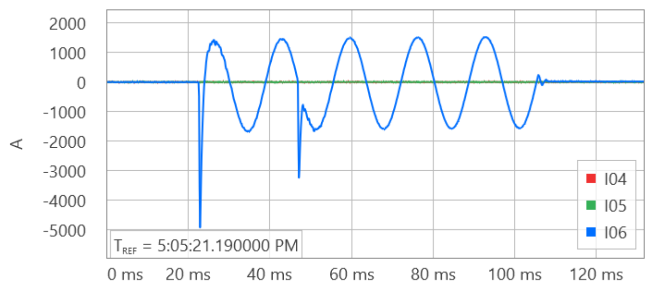
F. *Sub A–Sub C Line Protection Trip Analysis*

After the event analysis described in Subsections B through E was nearly complete, the protection engineers discovered in the events received from the field that the 87B2 bus protective relay had additional events, demonstrating that another fault had occurred between the time that the Sub A bus cleared and the time that it was restored to service. There was no other indication that this fault happened from the system operators or the technicians in the field. Of course, this event would eventually have come to light since the Bkr 6 operation at the other end of the line at Sub C would have had to be documented.

At 17:05:21 lightning struck the Sub A–Sub C line on C-phase, which was open at the Sub A end of the line and closed from the Sub C end of the line, as shown in Fig. 14. The lightning surge caused Bkr 2 to flash over. The 87B2 relay detected the internal fault and attempted to trip the Sub A bus even though the bus was already open. The fault was cleared after five cycles when the remote end of the line opened the breaker at Sub C.

The initial high-frequency current transient shown in Fig. 14a was due to a lightning strike on the line that flashed over in the breaker. After the lightning surge initiated the flashover in the breaker, the remote end of the line continued feeding the fault in the breaker until the remote end of the line opened. Fig. 14b demonstrates that the 52A contacts of every breaker on the bus were open at the time of the fault in Bkr 2, showing that the bus was open at this time. The 87B1 relay did not see this second fault because it was still shorted by the 86B LOR, which was still rolled. At 17:05:22, Bkr 6 at Sub C successfully reclosed.

a)



b)

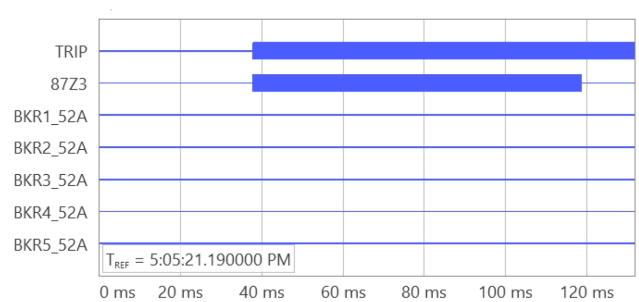


Fig. 14. Second fault while the Sub A Bus was open.

Only the history event file was available in the line relays on the Sub A–Sub C line. Table III shows the relevant information from the legacy relay's event history data. These were the only two records for the date of the fault. From this historical information, it is clear that the legacy line relays did detect the reverse BG fault at 16:37:00 and also saw something occur at 17:05:21. What the legacy line relays saw is not known since the event records and the SER records were not available. Because the legacy line relays did see something at 17:05:21, the flashover in the breaker must have been across the contacts of the breaker as well as to the ground.

TABLE III
LEGACY LINE RELAY PROTECTING SUB A–SUB C LINE EVENT HISTORY INFORMATION

Date	Time	Event	Location
6/27/23	17:05:21.250	ER	$$$$$$*
6/27/23	16:37:00.557	BG	-9.65

* The relay fault location did not run successfully.

G. *Lightning Report Data for the Second Fault*

Table IV shows the relevant lightning information from the same lightning report mentioned in Section E previously. Two lightning strikes occurred within 417 ft of the Sub A–Sub C line. This lightning report again demonstrates a strong correlation between the two high-frequency current transients in the relay event and the lightning report.

TABLE IV
LIGHTNING STRIKE DISTANCE FROM THE LINE FAULT TWO

Lightning Strike Time	Approximate Distance From Sub A (mi)	Approximate Distance From Line (ft)
17:05:21	3.84	417
17:05:21	3.84	103
17:05:21	NA*	NA*

* In this case, the lightning strike was in a random direction in relation to the substation and was nowhere near the transmission line.

V. DISCUSSION AND LESSONS LEARNED

A. Benefit of Multiple Operating Principles

This event is an excellent example of how different protection principles complement each other. The high-impedance bus differential relay detected the lightning strike flashover in the breaker since its filtering is designed to convert the currents from the saturated CTs into a phasor magnitude. The lightning strike impulse more closely resembles the voltage signature that the high-impedance bus differential relay is designed to operate on. The percentage-restrained relay supplied the high-resolution event reports that showed which signal caused the high-impedance relay to trip. Because each current channel is a separate input to the percentage-restrained bus differential relay, it revealed which current channel contained the high-frequency lightning transients and, therefore, which breaker failed. The percentage-restrained bus differential relay also recorded the later fault within the bus's zone of protection and revealed the second damaged breaker.

B. Depth of Event Analysis

Another important point this event demonstrates is that, most likely, not every detail of an event is known from the initial information given by the system operators, technicians responding to the event, and brief initial relay event analysis. In this case, some of the initial information led to incorrect assumptions about what had happened during the event. These incorrect assumptions had to be disproven by the event analysis before the actual equipment damage from the lightning strikes could be proven. Timely and thorough event analysis is critical to find hidden pieces of information, such as silent and subtle equipment failure.

C. Lightning's Effect on the Line and Breakers

The basic insulation level (BIL) rating of the transmission line insulation connecting to Sub A is 1,105 kV. The BIL rating for Bkr 2 and Bkr 3 was only 900 kV, with no surge arresters on any of the transmission lines at Sub A. This arrangement made the circuit breakers the weakest link. Additionally, being in the open position following the initial 16:37:00 fault caused the lightning impulses to double when they reflected at the dead end formed by the open circuit breaker.

When Bkr 3 was removed from service and inspected, no visible damage was found. A gas sample from the breaker was also taken at that time, and the gas analysis seemed normal. The breaker was still taken out of service and replaced according to the manufacturer's recommendation. Then it was cleaned and reserved as a spare breaker.

When Bkr 2 was removed from service and inspected, visible burn marks were observed on the breaker's C-phase contact, as shown in Fig. 15. The gas sample taken from this SF6 breaker indicated that the breaker was damaged. Unlike Bkr 3, Bkr 2 sustained not only the high-frequency current transients from the lightning strikes, but also five cycles of fundamental frequency fault current. This caused much more damage to Bkr 2 than the high-frequency current transients alone did to Bkr 3.

Fig. 15. Bkr 2 damage caused by lightning.

The breaker manufacturer was involved in the breaker failure analysis and recommended neither breaker be returned to service. Bkr 3 only experienced lightning flashover with no 60 Hz current reinforcing the breakdown to cause further damage to the breaker. Bkr 2 suffered lightning strikes as well as the internal fault for five cycles.

D. Steps Taken to Prevent Breaker Failure From Lightning Strikes on the Line

There is no method available to provide 100 percent shielding against direct lightning strikes on substations and transmission lines. As previously mentioned, none of the 230 kV transmission lines had shield wires when the event occurred. This information was not known or required during the event analysis, but it demonstrates how these two lines were not protected from the lightning strikes.

Prior to the event, the utility's standard practice was to not install lightning arresters on transmission lines due to the historically low total lightning density in their service territory. Based on this event, and the increasing lightning risk to the utility's 230 kV transmission system, a program was developed to install lightning arresters on breakers and to install shield wires on transmission lines.

VI. Conclusion

Faults on the power system happen all the time. Many times, the events only require a simple relay event analysis to verify that the Protection System operated correctly. When the details of an event are not fully known, a deeper event analysis is recommended to ensure as much information as possible is gathered about the event.

In the event analysis presented in this paper, the full details of the event were found by carefully analyzing the usual filtered event reports as well as the unfiltered, high-resolution event reports. This provided a much clearer view of what happened on the system and revealed the damage to the breakers from the lightning strikes. Eventually, the breakers would have failed and resulted in a larger effect on the BES. This event also demonstrates one example of complementary protection principles in action.

VII. References

[1] K. Behrendt, D. Costello, and S. Zocholl, "Considerations for Using High-Impedance or Low-Impedance Relays for Bus Differential Protection," proceedings of the 35th Annual Western Protective Relay Conference, Spokane, WA, October 2008.

[2] H. J. Altuve Ferrer and E. O. Schweitzer, III (eds.), *Modern Solutions for Protection, Control, and Monitoring of Electric Power Systems*, Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2010.

[3] R. Lings, *EPRI AC Transmission Line Reference Book—200kV and Above,* 3rd ed., Electric Power Research Institute (EPRI), Palo Alto, CA, 2005.

[4] "The Annual Lightning Report 2023," Vaisala, 2023. Available: www.xweather.com/annual-lightning-report?&utm_source=vaisala.com&utm_medium=referral&utm_campaign=annual-lightning-report-2023&utm_content=/en/products/national-lightning-detection-network-nldn.

VIII. Biographies

Robert Roman received his BS in electrical engineering from the University of Idaho in 2016 and a certificate in power systems protection from the University of Idaho in 2021. Robert previously worked as an electrical engineer at the Columbia Generating Station in Richland, Washington and joined the Avista Utilities Protection Engineering group in 2020. Robert is a registered professional engineer in Washington State.

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 Master of Engineering in Transmission and Distribution Engineering from Gonzaga University in 2020. In 2002, he joined Schweitzer Engineering Laboratories, Inc. (SEL) 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 Utilities in 2010 in the System Protection group where he currently is the system protection manager. Kevin has broad experience in the field of power system operations, maintenance, and protection and has authored and 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.

Emma Clawson received her BS in electrical engineering, summa cum laude, from Washington State University in 2021. In 2020 she was hired as an intern at Schweitzer Engineering Laboratories, Inc. (SEL), where she transitioned to working as a power engineer in 2021. She has also worked briefly for Avista Utilities as part of an engineering development exchange program between Avista Utilities and SEL.

20250612 • TP7160-01