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Line Current Differential Relay Response to a Direct Lightning Strike on a Phase Conductor

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Abstract—This paper describes an event in which lightning struck and discharged current into the phase conductor of a 345 kV transmission line. The magnitude of the lightning discharge was insufficient to lead to a flashover (line insulation breakdown). The paper examines and explains the response of two different line current differential protective relays to this event that was inside their zone of protection.

I. INTRODUCTION

On February 19, 2017, powerful storms and tornadoes swept through the state of Texas, damaging homes and properties in their path and leaving thousands of residents without power [1]. At the height of the storm, severe wind gusts bent at least one high-voltage transmission tower in half, as shown in Fig. 1.



Fig. 1. High-voltage transmission tower damaged during storm

The severe weather was accompanied by lightning. One of the lightning events affected a 345 kV, 5.6-mile transmission line that connects an 800 MW generation facility to the Texas power grid. The generating station was offline at the time of the event, meaning the line was in service but effectively open at the generating station end (feeding a very light station service load). The lightning strike directly struck the Phase A conductor (shielding failure) and discharged current into it. The line is protected by two different sets of line current differential relays used in a dual-primary scheme. Throughout the paper, we refer to the relay sets (two different models) as Type A and Type B.

The Type B line current differential relays operated in response to the direct lightning strike while the Type A relays did not.

Analysis of the relay event reports and data from the U.S. National Lightning Detection Network (NLDN) revealed that the magnitude of the lightning discharge was insufficient to lead to an insulation breakdown. However, the lightning strike created a differential current, like that of a short-circuit fault inside the zone of protection. The negative-sequence differential element in the Type B line current differential relays was set extremely sensitively to detect high-impedance internal faults and to operate instantaneously. As a result, it responded to the differential current and issued a trip.

In this paper, we share details about this event and analyze the relay event reports to understand what happened. We explain the different responses of the line current differential relays. Finally, we discuss the expected response of a protective relay to this disturbance and the factors that must be taken into consideration when reviewing relay settings after an operation.

II. BACKGROUND INFORMATION

To gain a better understanding of the event analysis presented in this paper, an overview of lightning, the equipment used to detect lightning, and the interaction of lightning with the power system is given. In addition, the paper reviews the characteristics of line current differential relays.

A. Mechanism of Lightning

Lightning occurs when electric charges separate inside a thundercloud, also known as a cumulonimbus cloud. The upper parts of the thundercloud contain positive charges while the lower parts of the cloud contain negative charges, with a small pocket of positive charge at the base (see Fig. 2) [2].

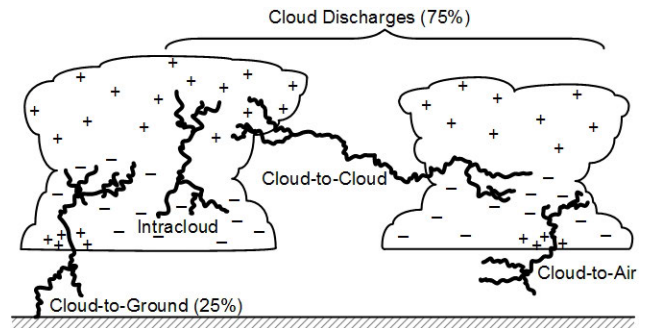


Fig. 2. Types of lightning discharges

Lightning discharge can occur between the different charge regions inside a single thundercloud (intracloud lightning), between two thunderclouds (intercloud lightning), between the cloud and air, or between the cloud and earth (cloud-to-ground lightning). Intracloud, intercloud, and cloud-to-air discharges are collectively referred to as cloud flashes.

Cloud-to-ground lightning strikes constitute about 25 percent of all lightning strikes and are a cause for concern because they can disrupt power systems [3] [4]. Such strikes can transfer a positive or negative charge to the ground and may originate from the cloud or from the ground. Consequently, cloud-to-ground lightning has four discharge types, as shown in Fig. 3.

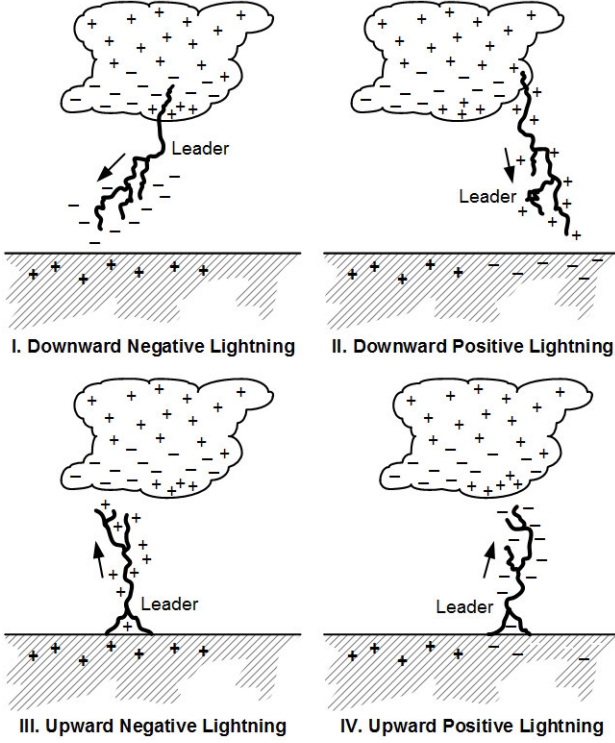


Fig. 3. Types of cloud-to-ground lightning

Almost 90 percent of all cloud-to-ground lightning strikes belong to Category I (negative downward), where an initial breakdown inside the cloud leads to a strong concentration of negative charge at the base of the cloud. The negative charge starts ionizing the air and a column of negative charge, referred to as the leader, starts moving from the cloud toward the ground. As the leader approaches ground, it induces streamers of opposite charge to rise from the ground toward the stepped leader. When the leader and streamer meet, the path between the cloud and ground is complete and a high-discharge current, known as the return strike, flows between the cloud and the ground. The median current value of the first strike is typically around 30 kA. The initial strike may be followed by several subsequent strikes that do not necessarily land at the same location as the original strike. The median current value of subsequent strikes is much lower than the first strike, typically 12 kA. A flash, which is a collection of three to five strikes, can last up to half a second.

Positive downward cloud-to-ground flashes (Category II) deliver a positive charge to the ground and are not very common. Tall objects with sharp corners at the top or mountain peaks can often initiate upward moving leaders, which can be positive or negative (Category III or Category IV). When those leaders reach the cloud, a lightning discharge follows. Since transmission lines and substations do not have sharp corners at the top, it is more common for them to experience downward flashes [5].

B. The U.S. National Lightning Detection Network

Vaisala, Inc., owns and operates the NLDN, which monitors all lightning activity in the U.S. 24 hours a day, 7 days a week. It does so by deploying more than 100 lightning detection sensors at strategic locations across the U.S., as shown in Fig. 4.



Fig. 4. Lightning sensors deployed by Vaisala across the U.S. [6]

Sensors that are triggered during a lightning strike record the electromagnetic pulses and send the raw data to a central location in Tucson, Arizona, via a satellite-based data acquisition system. The central processor combines data from several sensors to identify the peak current, location, date, time stamp, and type of lightning strike (cloud flash or cloud-to-ground). Reference [6] explains how the peak current is estimated from the electromagnetic pulse. In addition, strikes are assigned to a given flash if they occur within 6 miles and 500 milliseconds of the first strike, and if the 50 percent confidence ellipses drawn around the location of the two strikes overlap [7]. The information is then made available to real-time users, such as the National Weather Service, within 30 to 40 seconds of the lightning event. It is also archived in a permanent database for users to access later [8].

The annual cloud-to-ground flash density observed by the NLDN for individual states is available to the public [9]. Data for Florida and Texas, the two states that witness the most annual lightning events, are shown in Table I.

TABLE I
CLOUD-TO-GROUND FLASH DENSITY REPORTED BY THE NLDN [9]

State	Average Flashes Per Year	Flashes Per Square Mile Per Year
Florida	1,193,735	20.8
Texas	2,992,944	11.3

Flash density in the immediate vicinity of the affected line is close to 12.4 flashes per square mile per year. Published data also show that February is the “quiet” month in Texas (0.5–1.2 flashes per square mile per year) with May and June being the most active months [10].

C. Effect of Lightning on Transmission Lines

There are two kinds of lightning strikes on transmission lines—direct and indirect [11]. A direct lightning strike occurs when cloud-to-ground lightning terminates on a phase conductor or on a tower. Indirect lightning strikes, on the other hand, do not directly inject current into the transmission line conductors or the tower structure. Rather, the voltage and current are induced into the power lines by nearby cloud-to-ground lightning strikes or intercloud flashovers. Since direct strikes are responsible for causing faults on transmission lines, they are discussed in more detail in this section.

When lightning terminates on a phase conductor, it injects current into the line. The injected current divides into two equal parts and travels in both directions from the strike point toward the line terminals as current traveling waves. This is illustrated in Fig. 5.

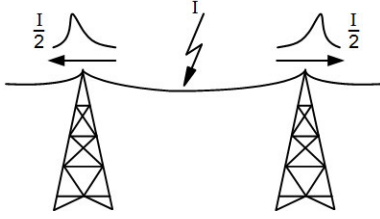


Fig. 5. Illustration of a direct strike to phase conductor

The voltage generated by the current traveling wave is given by (1).

$$V = \frac{Z_C I}{2} \quad (1)$$

where:

V is the voltage generated by the current traveling waves.

Z_C is the characteristic impedance (surge impedance) of the line.

I is the magnitude of the injected current.

If the voltage developed due to the injected current exceeds the insulator critical flashover voltage (CFO), a flashover will occur, resulting in a conventional short-circuit fault [12].

When lightning strikes the tower, the current surge travels through the tower to the ground. The current flowing through the surge impedance of the tower and the tower footing resistance develop a voltage rise across the tower crossarm. If the voltage difference between the tower crossarm and the phase conductor is large enough, a flashover will occur from the tower to the conductor across the insulator string. This is commonly referred to as a backflash event. The power system consequences are the same as for a strike on the phase conductor, with the backflash creating a short-circuit fault.

Ground wires (shield wires) are often placed above the phase conductors to reduce the possibility of a direct lightning strike to the phase conductors. Shield wires also reduce the possibility

of a backflash as the injected current is divided into three parts (tower and each direction on the shield wire).

Even with shield wires in place, lightning may strike the phase conductors. This is considered a shielding failure. Depending on the lightning current level, a shielding failure does not always result in a flashover. Strictly speaking (according to lightning-related literature), a direct strike to the phase conductor that does not result in a flashover is not considered a shielding failure because it does not cause a power system fault. From a protection point of view, the shielding did not protect the transmission line phase conductors from a direct lightning strike. Accordingly, we use the term “shielding failure” to include all direct phase conductor strikes. The minimum current required to initiate a flashover is given by (2).

$$I_C = \frac{2 \cdot \text{CFO}}{Z_C} \quad (2)$$

where I_C is the critical flashover current [4].

The CFO is a function of the lightning wavefront rise time, insulator geometry, air pressure, and other factors, but a ballpark estimate can be made from the basic insulation level. A typical CFO for a 345 kV line is around 1.8 MV. Using the high-frequency surge impedance for the line described in Section III (approximately 300 Ω), we can calculate the critical flashover current I_C as shown in (3).

$$I_C = 2 \cdot 1.8 \text{ MV} / 300 \Omega = 12 \text{ kA} \quad (3)$$

Comparing this result with the strike current distribution given in [12] and shown in Fig. 6 allows us to determine that lightning strikes with current lower than or equal to 6 kA occur in approximately 1.4 percent of all lightning strikes. With the cutoff limit set to 12 kA (critical flashover current level I_C calculated for this line), the probability curve climbs to 7.8 percent.

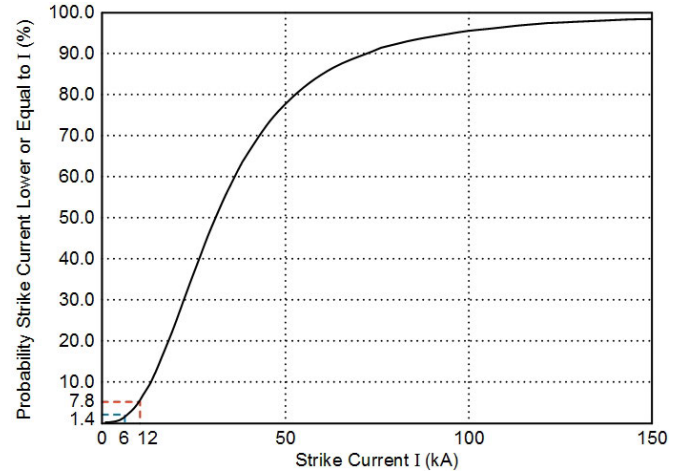


Fig. 6. Lightning strike probability as a function of strike current

Since the probability of a direct lightning strike cannot be eliminated even with the best shielding schemes, it is worth taking a more detailed look at the shielding properties of this line. Reference [12] teaches how to estimate the shielding

failure rate (SFR) for a 5.6-mile line exposed to approximately 11.3 flashes per square mile per year (per Table I). Full analysis goes well beyond the scope of this paper, with results strongly dependent on the analysis model used. We will, however, venture to say that our calculations per [13] point to SFR numbers in the order of 0.03 to 0.07 strikes per 100 miles per year. For a 5.6-mile line, this translates to 0.0017 to 0.004 strikes per year, or approximately one direct lightning strike to a phase conductor occurring without a flashover (2 to 12 kA) every 250 to 588 years.

D. Line Current Differential Protection

Current differential protection is based on Kirchhoff's current law, which states that the sum of all measured currents that make up a protected zone must equal zero, with the protected zone being defined by the location of current transformers (CTs). If this condition is not met, there is another path that is diverting current away, such as an internal fault. Differential protection is selective, sensitive, simple, and fast, and it is commonly used to protect buses, transformers, generators, and transmission lines.

When applied to transmission lines, current differential protection requires a communications channel to receive currents from the remote terminals. Fig. 7 shows differential protection being applied to a two-terminal transmission line. One relay measures current at the local terminal while the other relay measures current at the remote terminal. The two relays then exchange current information over the communications channel to calculate the difference current (I_{OP}). If I_{OP} is greater than a pickup threshold and the ratio of the remote current to the local current plots outside the restraining region shown in Fig. 8, the relay operates. Refer to [14] for more information about differential relay principles and their application.

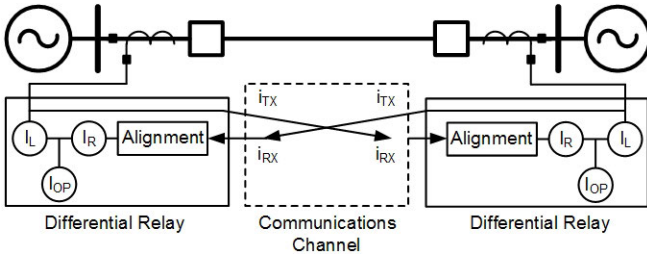


Fig. 7. Example two-terminal system

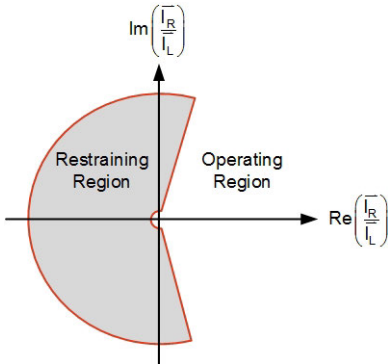


Fig. 8. Line current differential relay characteristic

1) Type A Line Current Differential Relay

The Type A line current differential relay is designed to protect two- or three-terminal transmission lines and has a differential element for each of the phase currents and a separate differential element for the negative- and zero-sequence currents. The phase current differential elements provide high-speed protection for high-magnitude faults, typically metallic faults, while the negative- and zero-sequence elements provide dependability for low-magnitude faults or high-resistance faults. The negative- and zero-sequence differential elements are very sensitive but are susceptible to CT saturation during external faults. Therefore, these elements need to be secured during external fault conditions. High harmonics in the differential current indicate that at least one of the CTs is in saturation. For this reason, the Type A relay adds a delay of 1.25 cycles to the sequence elements so that it can measure the harmonic content of the differential current and restrain the operation of the differential element when high harmonic content is detected [15].

2) Type B Line Current Differential Relay

The Type B relay is more advanced than the Type A relay and can protect up to four-terminal transmission lines. It also includes a traveling-wave fault locator (TWFL) and uses advanced algorithms to improve differential element security during external faults. One such advancement pertains to how this relay secures the negative- and zero-sequence differential elements against CT saturation during an external fault. The Type B relay does not delay the sequence elements and wait for CT saturation to take place. Instead, it uses logic to detect an external fault before one of the CTs saturates (typically within the first 3 milliseconds of the fault) and secures the element by boosting the restraint quantity, increasing the pickup threshold and expanding the restraining region in anticipation of CT saturation. The external fault detector logic is described in detail in [16] and [17].

III. THE OUTAGE

Fig. 9 shows the one-line diagram of the power system and indicates that all breakers were closed at the time of the event. Transmission lines T1 and T2 carry electric power generated by the 800 MW combined-cycle gas power plant from Substation Delta to Substation Charlie from where power is transmitted through the grid to serve customers in Texas.

Transmission lines T1 and T2 are 5.6 miles long and are constructed as a double circuit on a single tower, as shown in Fig. 10. Since the state of Texas experiences significant lightning activity, the transmission lines are protected by two shield wires. The transmission line towers are relatively tall, with shield wires at 135 feet above ground. The shielding angle (α) of 12.5° far exceeds the commonly used 30° angle requirement. More precise calculations of shielding angle that consider terrain, tower height, and the lightning current level can be found in [12] and [18].

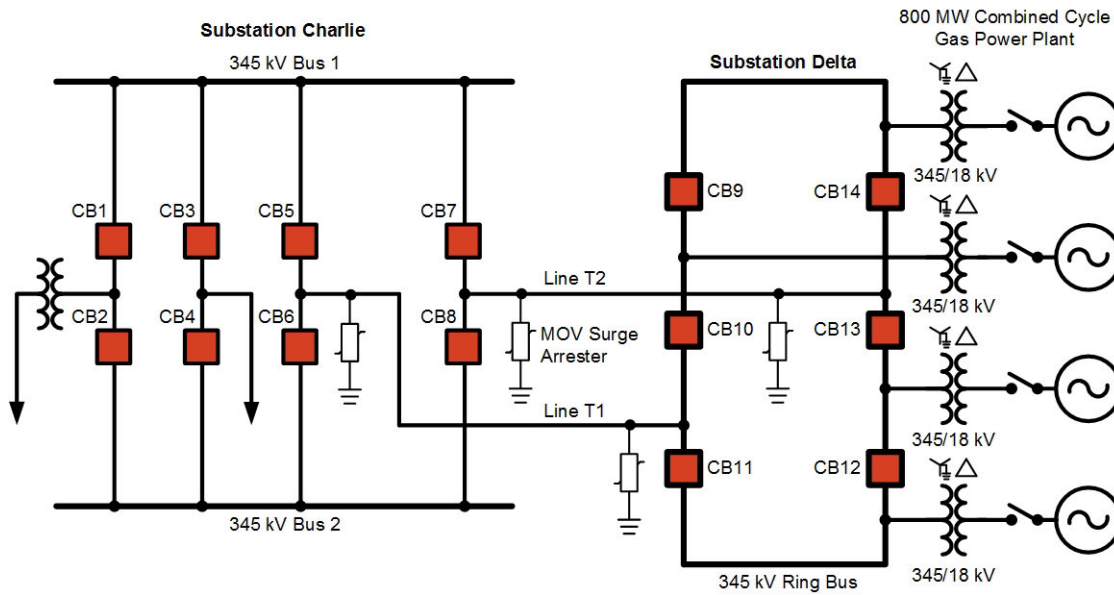


Fig. 9. Simplified system diagram

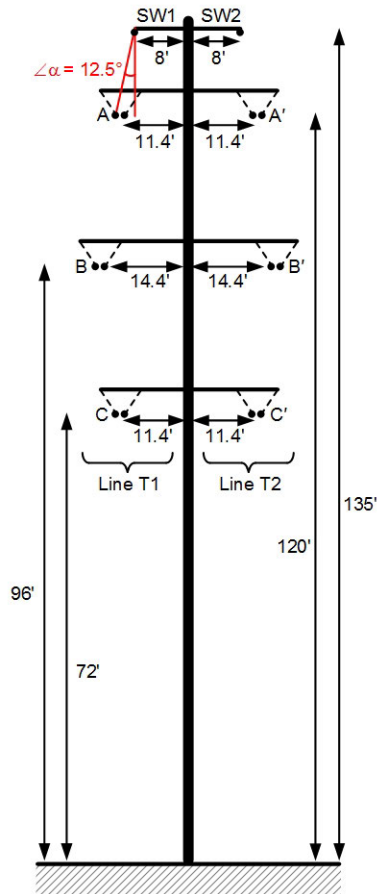


Fig. 10. Tower geometry of the 345 kV transmission lines between Substations Charlie and Delta

Metal-oxide-type surge arresters are installed at the Charlie and Delta substations to protect substation equipment from overvoltage conditions caused by switching or lightning strikes [19]. There are no additional surge arresters along the physical transmission line. At the time of the event, both lines T1 and T2 were in service with negligible power consumption (essential station service) at the power plant end of the line. The disconnect switches were open, isolating the generators.

On February 19, 2017, at 23:29, the Type B line current differential relays protecting Transmission Line T1 issued a trip and locked out circuit breakers CB5, CB6, CB10, and CB11. The Type A line current differential relays protecting the same transmission line in a dual-primary scheme did not initiate a trip. System operators closed the line 14 minutes later. The line outage did not affect customers because the 800 MW power plant was offline at the time of the event.

Because of adverse weather conditions on the day of the event, utility engineers checked the NLDN database for lightning activity around the time of the relay operation. The data, summarized in Table II, showed that there had been two negative lightning strikes. Recall from Section II that most cloud-to-ground strikes are of this type. A multiplier equal to zero in the table indicates that the strikes were not part of the same flash, but rather two separate strikes.

TABLE II
SUMMARY OF LIGHTNING DATA FROM THE NLDN

Strike	Date and Time	Discharge Type	Signal (kA)	Multiplier
1	2/19/2017 23:29:06.798	Cloud-to-ground	$12 \pm 15\%$	0
2	2/19/2017 23:29:07.196	Cloud-to-ground	$6 \pm 15\%$	0

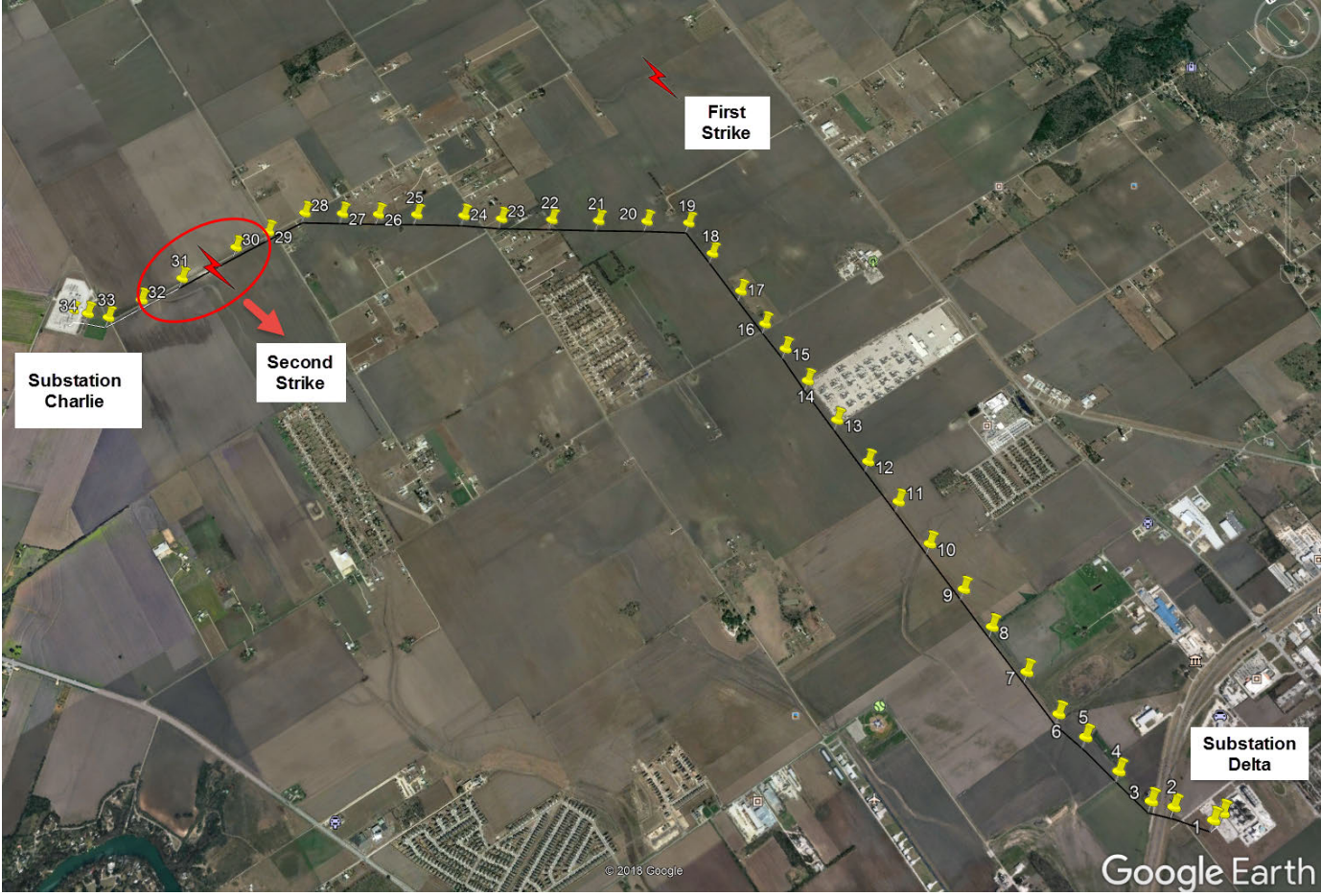


Fig. 11. Lightning activity detected at the time of the relay operation (double-circuit towers carrying Lines T1 and T2 are shown as yellow pushpins)

One strike occurred at 23:29:06.798 at a location far from the transmission line, as shown in Fig. 11. The peak current delivered by the strike was reported to be 12 kA, ± 15 percent. The 15 percent median error of the sensors in estimating the peak current was reported in [20]. Another strike occurred at 23:29:07.196. The peak current delivered by the strike was reported to be 6 kA, ± 15 percent. The second strike was found to have contacted the ground somewhere inside the detection ellipse drawn to match the NLDN 99 percent confidence level.

Because transmission line towers 29 to 32 are within the confidence ellipse, it is clear that the second strike played a key role in the relay operation. This theory is corroborated by the time stamp of the relay operation at 23:29:07.116028, which coincides with the second event. The lightning strike location estimate from the TWFL in the Type B relay is 0.5 miles. This translates to a location between Tower 31 and Tower 32, which falls inside the detection ellipse drawn in Fig. 11 and further backs up the theory.

While data from the NLDN helped to identify lightning as the root cause of the relay operation, several questions were raised as to whether lightning struck the ground or the phase conductor, whether the lightning strike led to a flashover, and whether the relay operation was correct. We attempt to answer these questions in the next section.

IV. EVENT ANALYSIS

When a Type B differential relay trips, it captures an oscillographic event report of the voltages and currents at the time of the trip and the status of the relay protection elements. These data are saved in raw and filtered formats. Raw event reports show voltage and current waveforms that have passed through an analog low-pass filter and have had all frequencies greater than 3 kHz attenuated by 50 percent or more. The filtered event reports show voltage and current waveforms that have passed through two additional filters, a digital antialiasing and a digital band pass filter (DBPF), and contain only 60 Hz information. The Type B relay is also equipped with a TWFL, which records data at a sampling rate of 1.5625 MHz. Data recorded in the TWFL report is high-pass filtered, meaning that frequencies below 1 kHz are attenuated. Together, the raw and traveling-wave data provide a complete picture (all-frequency spectrum) of the actual signal seen by the relay, while the filtered event report is useful when analyzing the current differential element operation. In this section, we analyze the raw, traveling-wave, and filtered event reports from the Type B relay to gain insight into the event and answer the questions raised in the previous section.

A. Raw Event Report Analysis

Because the generating station at Substation Delta was offline at the time of the event, we look at the raw data captured by the Type B relay at Substation Charlie. The voltage and current waveforms are shown in Fig. 12. The Type B relays in this event were programmed to save data at 2 kHz (these relays allow users to save data at a sampling rate of up to 8 kHz). While the lower sampling rate is adequate for analyzing 60 Hz events, it is not ideal for visualizing fast transients.

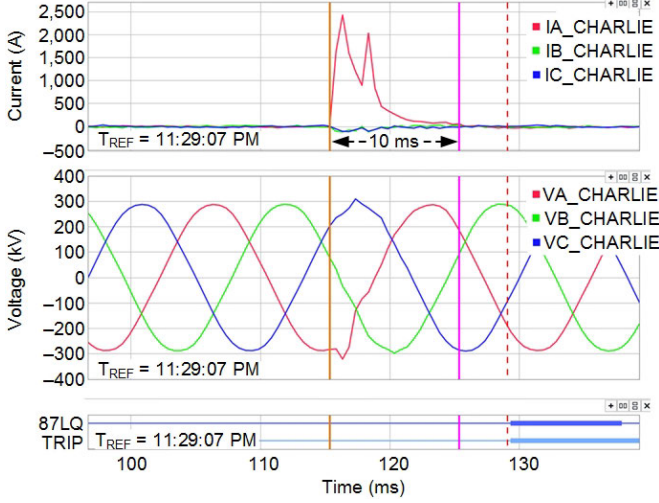


Fig. 12. Event data recorded at Substation Charlie with a resolution of 2 kHz

Starting at 23:29:07.116028, the relay at Substation Charlie observed a high current on Phase A for a very short duration. The negative-sequence differential element (87LQ) operated on this unbalance and tripped the line 14 milliseconds later. The current spike lasted for about 10 milliseconds and was not followed by a 60 Hz current, meaning that the lightning strike in this event did not flash over and cause a power system fault. This is further corroborated by the increase in Phase A voltage at the time of the current spike. For a conventional 60 Hz short-circuit fault, we expect the voltage of the faulted phase to sag, not swell. The result is also consistent with the theory that lightning strikes with currents less than the critical current do not cause a flashover. Recall that the NLDN reported the peak current of the lightning strike to be approximately 6 kA, ± 15 percent, which is less than the critical current for this line (12 kA).

The waveform of the Phase A current leaves quite a few unanswered questions about the real nature of the event. Correlating the time stamp of this event with the NLDN report in Table II allows us to say with confidence that this event had something to do with lightning. But, it also leaves us with the realization that the 2 kHz recording in Fig. 12 does not contain sufficient information about the lightning strike. To make things more confusing, lightning strike current is normally much shorter than the recorded 10 millisecond spike. As with any natural process, lightning current varies a lot but is typically represented with an exponential wave having a $1.2 \mu\text{s}$ rise time and $50 \mu\text{s}$ fall time. This duration is almost 200 times shorter than the event recorded in Fig. 12.

To gain a better understanding of the event, we need an event report that has a much higher sampling frequency. Fortunately, the Type B relays are equipped with a TWFL and can record a separate traveling-wave report at a sampling rate of 1.5625 MHz. The traveling-wave report is analyzed in the next subsection.

B. Traveling-Wave Event Report Analysis

Fig. 13a shows the Phase A traveling-wave currents that the Type B relays recorded at both ends of the line. For ease of use, they have been plotted on the same graph. Data are synchronized via GPS with submicrosecond accuracy, allowing an accurate representation of the wave travel times. Fig. 13b zooms into the initial wave received at both terminals. Notice that both terminals recorded a high-current pulse on Phase A. Traveling waves on Phases B and C had lower magnitudes and polarities opposite to those of Phase A, confirming that this was a direct strike to the Phase A conductor (shielding failure) [21].

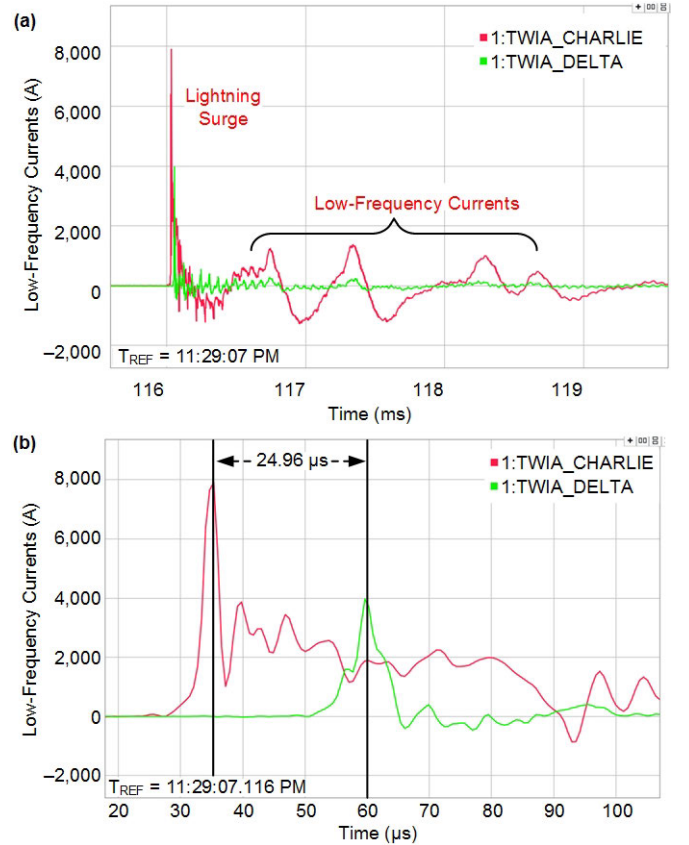


Fig. 13. Phase A traveling-wave currents at both line ends (a) and a zoomed-in view of the first strike (b)

Another point of interest is that the current traveling waves (TWIA) recorded at either terminal of the transmission line have the same polarity, and the time difference ($\Delta t = 24.96 \mu\text{s}$) between the arrival of the two current TWs at their respective terminals is less than the traveling-wave line propagation time ($\text{TWLPT} = 31.15 \mu\text{s}$). This indicates that the lightning strike was inside the zone of protection between the line terminals.

Analysis of the traveling-wave event report so far helped piece together some of the missing pieces of the puzzle. For example, we learned that this event was indeed a shielding

failure and lightning had struck the Phase A conductor. From the analysis in the prior subsection, we had concluded that this lightning strike had not led to a flashover (no 60 Hz current).

We now focus our efforts in understanding the succession of low-frequency traveling-wave currents seen by the relay at Substation Charlie (see Fig. 13a) after the initial lightning strike. The currents get slowly damped but remain visible for a full millisecond. Additional discussion showing how a 50 μ s lightning impulse got converted into a low-frequency transient lasting long enough (10 milliseconds) for the protection elements to pick up is given in the next subsection.

C. Origin of the Low-Frequency Transient

To explain the low-frequency currents, it is important to understand the voltage developed on the line because it plays a significant role in helping explain this event and the behavior of the protective relays. Since no high-frequency oscillography of the voltages at the line terminals was available for this event, an electromagnetic transient program was used to model the transmission line and power system. However, due to the high frequencies involved, there is not sufficient detail available to accurately model the behavior of the power system during an actual lightning strike. Instead, the model was used to obtain an approximate (qualitative) voltage profile of the voltage that developed on the transmission line due to the lightning strike.

A lightning strike into the Phase A conductor was simulated using a CIGRE (International Council on Large Electric Systems) lightning current source model. The peak magnitude of the injected current is 8 kA. The line characteristic impedance (Z_c) for the simulated lightning strike, simulated by a 1.2/50 μ s pulse, is approximately 350 Ω . Therefore, an 8 kA, 1.2/50 μ s lightning strike develops a peak voltage of approximately 1,400 kV. The lightning strike was simulated to occur at the same instant the positive peak voltage occurred on Phase A (≈ 280 kV). Therefore, the peak instantaneous voltage is approximately 1,680 kV. The simulated lightning strike was injected at the same location as the second lightning strike shown in Fig. 11. The voltage profile at the point of current injection over a period of 80 μ s is shown in Fig. 14.

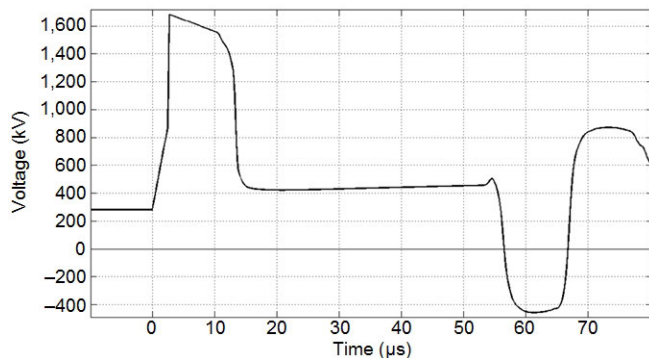


Fig. 14. Voltage profile at the current injection point.

Before the voltage traveling wave reaches the line terminal, it passes a surge arrester. The arrester clips and clamps the magnitude of the voltage traveling wave and diverts some of the injected current to ground. The voltage profile at Substation Charlie is shown in Fig. 15 (blue). The voltage at the injection point (black) is also shown.

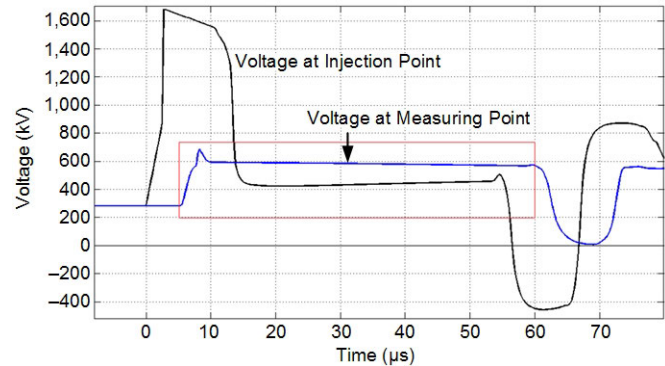


Fig. 15. Voltage profile at the current injection point (black) and at Substation Charlie (blue)

From Fig. 15, the impact of the surge arrester can be seen; it clamps the magnitude of the voltage traveling wave to approximately 600 kV. Since the line is very short (31.15 μ s), the arrester action is soon seen along the entire line length. Note that the voltage shown in Fig. 15 is the sum of the incident and reflected voltage. The power system impedance behind the relay measuring point at Substation Charlie determines how much of the incident voltage and current traveling waves are transmitted and reflected. The other terminal of the transmission line, Substation Delta, is effectively open. As a result, nearly all of the incident voltage at Terminal Delta is reflected into the line. The step change in terminal voltage at Substation Charlie, shown inside the red box in Fig. 15, is short-lived but stimulates (excites) the power system (resistors, inductors, and capacitors) behind the Substation Charlie line terminal. The low-frequency traveling-wave currents seen by the relay at Substation Charlie (Fig. 13a) are the response of the power system to that voltage stimulus. Since the generating plant end of the line (Substation Delta) is effectively open, we can see that there is no low-frequency current exiting this end of the line. Therefore, all of the low-frequency current measured at Substation Charlie is seen by the relays as differential current (difference between the red and green traces) originating inside the T1 line protection zone.

D. Relay Response to the Low-Frequency Transient

To understand the relay response, we attempted to reconstruct the actual current waveform on the power system and at the relay inputs before any kind of filtering. To do this, we upsampled the 2 kHz raw current data to 1.5625 MHz and combined it with the traveling-wave data. The result is shown in Fig. 16.

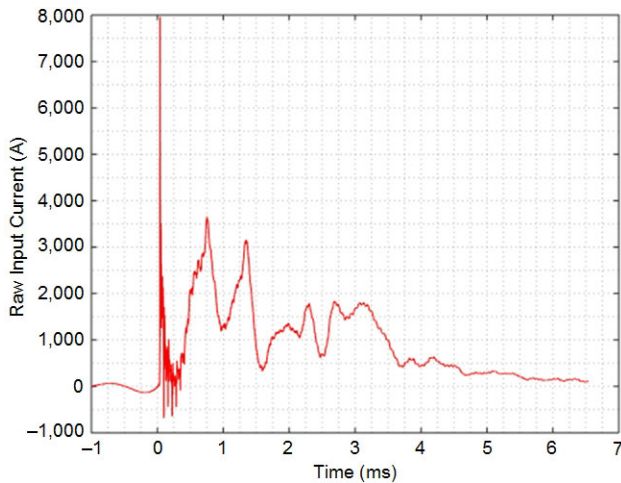


Fig. 16. Current measured by the relay at Substation Charlie before any filtering

If we do a frequency spectrum of the current in Fig. 16, we obtain the data shown in Fig. 17.

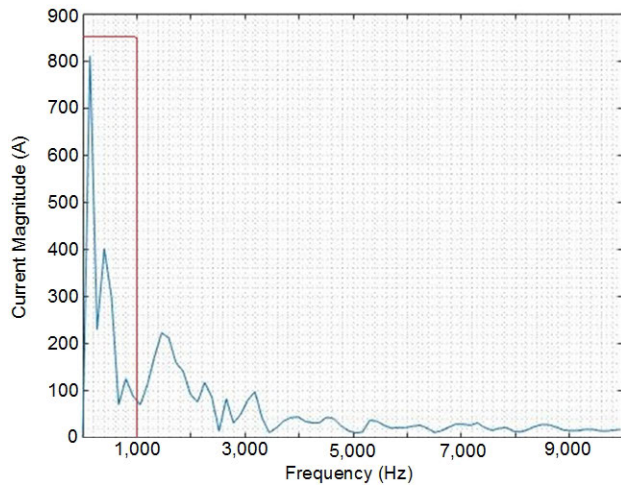


Fig. 17. Frequency spectrum of the current measured at Substation Charlie (note magnitude of the current below 1 kHz, shown inside the red box)

From this we can verify that the response current caused by the voltage stimulus contained frequencies from dc to tens of kilohertz, with portions of the higher frequency current transient being diverted by the surge arrester. The relays' analog and digital antialiasing filters effectively attenuate frequencies above 1 kHz. However, currents below 1 kHz (inside the red box in Fig. 17) pass through the antialiasing filters unaffected. Fig. 18 shows the output after the current in Fig. 16 has passed through the digital antialiasing filters in the relay.

After the current has passed through the digital antialiasing filter, the currents are input into a DBPF, and from this the nominal frequency component of the signal is extracted (in this case, nominal frequency is 60 Hz). Fig. 19 is the output of the 60 Hz DBPF at Substation Charlie. As noted earlier in this section, the line terminal at Substation Delta was open. This means there was very little current measured at this line terminal. Therefore, the phase differential current and the resulting negative-sequence differential current are approximately equal to the current measured at Substation

Charlie, as shown in Fig. 19. Because the pickup of the negative-sequence differential element was set very sensitively at 200 A primary, the measured negative-sequence differential current exceeded the pickup. We study the relay operation in more detail using the filtered event report in the following subsection.

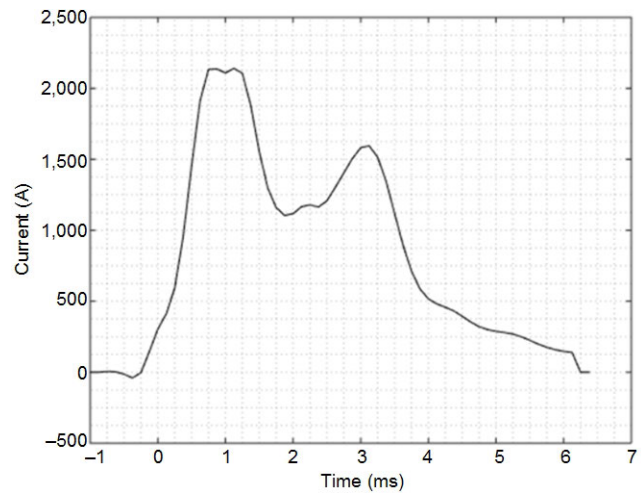


Fig. 18. Current after being filtered by the antialiasing filter (current is fed into DBPF)

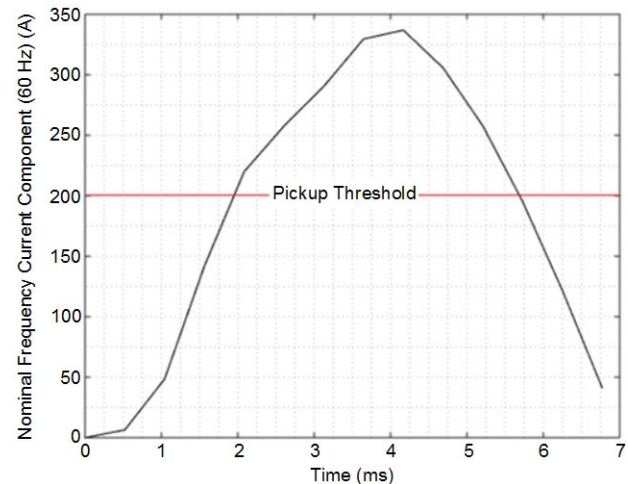


Fig. 19. 60 Hz output from the DBPF

E. Filtered Event Report Analysis

We use the filtered event report to explain the trip issued by the Type B line current differential relay. The lightning strike was inside the zone of protection. As a result, the external fault detector did not assert and the element continued to be in the normal/sensitive mode. Because the negative-sequence differential current (I_{OP}) measured by the relay during the disturbance was greater than the pickup setting of 200 A and the current ratio plotted outside of the restraining region, as shown by the orange point in Fig. 20, the negative-sequence differential element (87LQ) asserted instantaneously and caused a trip.

The Type A relays also measured the same negative-sequence difference current, but the inherent time delay in the negative-sequence differential element logic prevented the Type A relays from operating.

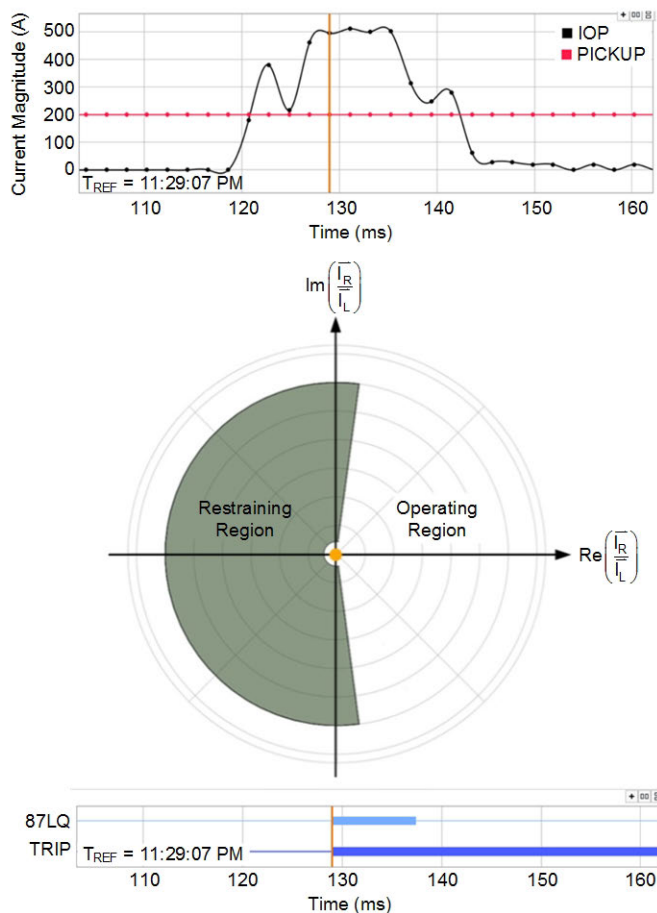


Fig. 20 Analysis of the Type B relay operation

V. DISCUSSION

The question now is, did the negative-sequence differential element in the Type B relay operate correctly for this situation? If not, what needs to be done to correct this situation?

From a current differential principle point of view, the relay operated correctly. The direct lightning strike into the phase conductor injected current at a nonmeasured point in the differential zone. The injected current developed a voltage that stimulated the power system to produce a current that contained fundamental frequency current. It is this fundamental frequency current that caused the negative-sequence differential element to operate. Fundamentally, this is very much like a self-clearing fault except that during a fault, current is sunk at the location of the fault on the transmission line. A trip followed by a reclose may be considered an acceptable response to the disturbance and requires no setting changes.

If the relay action is judged to be incorrect, the following two setting changes will prevent the negative-sequence differential element from tripping the line for similar events in the future.

- Increase the pickup of the negative-sequence differential element. To do this, the user will have to study the impact of a direct lightning strike to a phase conductor that does not result in a flashover (lightning strike below 12 kA for this line) under different power system configurations, determine the maximum negative-sequence current possible for all the scenarios, and set the pickup above this level. This is a nontrivial task and requires some detailed study. Furthermore, the task cannot be generalized and is highly dependent on the line construction, line length, terrain, and the lightning risk in the area. It is also important to point out that increasing the pickup could lead to losing dependability for high-resistance faults.
- Delay the negative-sequence element by half or one power system cycle, the only caveat being the purposeful delay of the negative-sequence element for internal faults. This may be an acceptable compromise because the purpose of the negative-sequence element is to detect high-impedance faults. For these fault types, sensitivity is more important than speed because these faults do not impact power system stability or damage power system equipment.

Protection engineers must also weigh the fact that direct lightning strikes to a phase conductor almost always result in flashovers. The event described in this paper is rare; this can be confirmed by estimating the shielding failure rate of a line, as explained in Section II. While the results strongly depend on the analysis model used, we can venture to say that approximately one direct lightning strike to the 5.6-mile line described in the paper will not flash over every 250 to 588 years. Although it would require additional simulation studies to positively prove the case, we believe that the differential zone current (low-frequency resonances excited by the lightning event) would have been significantly lower if the generating plant was in service, thereby allowing lightning energy to dissipate through both ends of the line. Does one event justify changing relay settings and sacrificing sensitivity or speed for a far more common occurrence—actual faults and short circuits (including high-impedance faults)—on the protected line? The right answer depends on protection philosophy and specific system conditions.

VII. CONCLUSION

Relay operations in general, and especially the unintended or surprising operations, are a treasure trove of useful information. They should be analyzed in detail to learn about the power system and identify improvements to relay protection. Modern protective relays offer unprecedented recording capabilities, often allowing us to look at the same event through multiple lenses.

The event presented in this paper was without a doubt a very rare and interesting event. Using data from the NLDN and traveling-wave oscillography from protective relays, we learned that lightning had struck the phase conductor of a transmission line (shielding failure) and injected current into it. The voltage that developed due to the injected lightning surge was not high enough to result in a flashover of the transmission line insulators. However, it stimulated the power system behind one of the transmission line current differential relays. The response of the power system to the voltage stimulus was a current with large low-frequency content. The nominal frequency (60 Hz) current content was large enough to create enough fundamental differential current to result in the operation of a sensitively set negative-sequence current differential element of one of the dual main protective relays.

Determining whether or not the operation of the negative-sequence element was correct depends on what is considered an acceptable response to a direct lightning strike inside the zone of protection. From a current differential point of view, the relay operated correctly. The event was much like a self-clearing fault, in which case a trip followed by a high-speed reclose is an acceptable response and does not require any setting changes. If the relay action is judged to be incorrect, the corrective action consists of increasing the pickup or delaying the negative-sequence differential element up to one power system cycle. The protection engineer must decide whether sacrificing sensitivity or speed is justified given the rarity of this event.

VIII. ACKNOWLEDGMENT

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XI. BIOGRAPHIES

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