NEPR

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**GOVERNMENT OF PUERTO RICO**
**PUERTO RICO PUBLIC SERVICE REGULATORY BOARD**
**PUERTO RICO ENERGY BUREAU**

| | |
|---|---|
| IN RE: INTERRUPCIÓN DE SERVICIO ELÉCTRICO DE 21 DE FEBRERO DE 2022 | **CASE NO. NEPR-IN-2022-0001**<br><br>**SUBJECT:**<br><br>**Submission of Public Version of Detailed Report on the February 21st Incident** |

**MOTION SUBMITTING PUBLIC VERSION OF DETAILED REPORT ON THE FEBRUARY 21$^{ST}$ INCIDENT**

**TO THE HONORABLE PUERTO RICO ENERGY BUREAU:**

**COME NOW LUMA Energy, LLC** ("ManagementCo"), and **LUMA Energy ServCo, LLC** ("ServCo"), (jointly referred to as the "Operator" or "LUMA"), and respectfully states and requests the following:

1. On February 22, 2022, this Honorable Puerto Rico Energy Bureau ("Energy Bureau") issued a Resolution and Order whereby it initiated an investigation of the incident that took place on February 21, 2022 ("February 22$^{nd}$ Order"). The incident caused the shutdown of certain generation units, including Central San Juan, Palo Seco, and Aguirre unit 2, operated by the Puerto Rico Electric Power Authority ("PREPA") (hereinafter, the "February 21$^{st}$ Incident"), and multiple outages of the electric system as well as service interruption for many customers in northeast Puerto Rico.

2. In the February 22$^{nd}$ Order, the Energy Bureau fixed February 25, 2022, as the date for LUMA to file a root cause report of the February 21$^{st}$ Incident. Specifically, it instructed LUMA to provide the following information:

i. a summary of the incident including, but not limited to, a chronological description of the events and their effect, if any, on PREPA's generation fleet, as well as investigative, corrective, or other actions taken by LUMA and PREPA;

ii. any information received, obtained, or gathered in the course of investigative, corrective, or other efforts undertaken by LUMA and/or PREPA, its agents, attorneys, or consultants to determine the cause of the incident and its effect, if any, on PREPA's generation fleet;

iii. Any document produced, prepared, or received by LUMA and/or PREPA, its agents, attorneys, or consultants in the course of investigative, corrective, or other efforts undertaken to determine the cause of the incident, including but not limited to, the root cause report of the incident and its effect, if any, on PREPA's generation fleet; and

iv. any information, data, video, audio, photos, report, or document submitted to federal or local authorities regarding the incident and its effect on PREPA's generation fleet.

3. On February 25, 2022, LUMA filed a *Motion Submitting Preliminary Report on February 21$^{st}$ Incident and Request for Confidential Treatment* ("February 25th Motion"). The February 25$^{th}$ Motion included as Exhibit 1 a preliminary public report of the February 21$^{st}$ Incident. The preliminary report included the information that LUMA had gathered thus far and preliminary findings and assessments of the February 21$^{st}$ Incident. However, given the nature of the February 21st Incident, LUMA was unable to provide at that time additional documentation to

the information submitted in the preliminary report. Therefore, LUMA informed that the detailed report on the incident would take an estimated six weeks.

4. On April 14, 2022, LUMA filed a *Motion Submitting Detailed Report on February 21 st Incident and Request for Confidential Treatment*, in which it submitted a detailed report of the February 21$^{st}$ Incident (hereinafter, the "Detailed February 21st Report"). The Detailed February 21st Report was based on the forensic analysis of the electrical system disturbance that caused a widespread power outage on February 21, 2022. It was filed under seal of confidentiality. Further, LUMA submitted to the Energy Bureau a public executive summary of the Detailed February 21$^{st}$ Incident Report.

5. On May 12, 2023, the Energy Bureau issued a Resolution and Order (the "May 12th Order"), whereby it adopted LUMA's Final Report and recommendations on the February 21st Incident and concluded that LUMA complied with the February 22nd Order. Nevertheless, the May 12th Order instructed LUMA to submit, on or before May 22, 2023, a public redacted version of the Detailed February 21st Report.

6. In compliance with the May 12th Order, LUMA hereby submits a public redacted version of the Detailed February 21st Report (attached hereto as Exhibit 1).

7. Considering the above, LUMA respectfully requests the Energy Bureau to close the instant proceeding.

**WHEREFORE,** LUMA respectfully requests that the Energy Bureau **take notice** of the aforementioned, **accept** the public version of the Detailed February 21$^{st}$ Incident Report included as Exhibit 1 of this Motion, and **deem** that LUMA complied with the May 12$^{th}$ Order.

**RESPECTFULLY SUBMITTED.**

We hereby certify that we filed this motion using the electronic filing system of this Energy Bureau and that we will send an electronic copy of this motion to the attorney for PREPA, Idelisa Carerro, icarrero@diazvaz.law.

In San Juan, Puerto Rico, this 22nd day of May 2023.


**DLA Piper (Puerto Rico) LLC**
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*/s/ Yahaira De la Rosa Algarín*
Yahaira De la Rosa Algarín
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*Exhibit 1*


LUMAPR.COM

# NEPR-IN-2022-0001

# Analysis for Disturbance Event on February 21, 2022

April 14, 2022

# Executive Summary

This report is based on the forensic analysis of the system's behavior during the electrical system disturbance that caused a widespread power outage on Monday, February 21, 2022.

LUMA is committed to being transparent with our customers and regulators about our operations and the successes and challenges we face in delivering more reliable energy. This report reflects LUMA's dedication to (1) highlight the significant challenges it continues to face as result of inheriting a Transmission & Distribution system that suffered from years – if not decades – of neglect; (2) address these legacy challenges through continuous improvement;  and (3) determine the root cause of widespread outages in order to identify actions to reduce the likelihood of future incidents and mitigate the impact on our customers.

Based on our extensive analysis of the February 21st, 2022, outage event, LUMA determined that the cascading failure was the result of substation equipment that had been subjected to years of neglect predating LUMA. While LUMA is proposing a series of short and long-term actions to help mitigate these types of large-scale events, it is important to note that these substandard and deteriorated conditions are prevalent throughout the transmission and distribution system. These operational conditions are the result of past neglect and mismanagement by the prior operator. This effort will last several years. Nevertheless, LUMA is working every day to address these serious legacy issues in an effort to repair, rebuild and stabilize the system over the coming months and years.

**February 21 Outage Event and Response**

The estimated number of customers affected by this outage was approximately 590,000, or 40.3% of the customer base. Due to the hard work and professionalism of our utility workers, LUMA, working in conjunction with Puerto Rico Electric Power Authority (PREPA) and other generators, was able to restore power to nearly all customers – or 98% of the total customers affected by the outage – within three hours. By 16:12 on February 21st, or approximately 3 hours after the event began, the number of customers without power was below 19,000 or 1.3% of the customer base. Following restoration, LUMA immediately began an investigation to determine the cause of the outage and define what steps may help prevent future outages of this kind.

**Identified Root Causes**

On February 21, 2022, at 13:19, a single phase-to-ground fault occurred on the 115 kV line 38100 from San Juan Steam Plant (SP) to Viaducto Transmission Center, approximately one mile from San Juan SP. The initial fault was the result of vegetation contacting the line, which was detected by the line relays at both terminals. While the circuit breaker at Viaducto TC operated correctly, the circuit breakers at San Juan SP failed to operate due to lack of direct current (dc) power supply caused by damaged wires. As a result, a single transmission line fault cascaded into a series of larger outages.

Utility industry standard regularly scheduled maintenance is intended to address potential damages that impact the breaker failure scheme at San Juan SP. Had the necessary circuit breakers opened, the fault would have been isolated locally at the substation. However, the breaker failure scheme at San Juan SP failed to operate (due to aged wiring) thus requiring all the 115 kV circuits from San Juan SP to operate at the remote end to clear the fault.

Additional issues were identified during the remote backup operations explained in this report, which resulted in subsequent outage events across the power system in Puerto Rico.

The report covers the known details of the four stages of the power outage, as described in further detail in Sections 2 and 3 of this report:

- Initial fault at line 38100 – Viaducto TC to San Juan SP.
- Circuit breaker failure event in San Juan SP.
- Unresponsive circuit breaker failure protection in San Juan SP and remote-end operations.
- System-wide disturbance.

Based on the review of the events and the data available, the forensic analysis indicates the following causes:

- Critical equipment had suffered from years of neglect or poor maintenance, which directly contributed to a series of cascading faults that led to a large-scale outage.
- Loss of dc on circuit breakers 31840-0084 and 0086 was responsible for delayed and non-selective fault clearing.
- The breaker failure protection (50BF-38140-0084) failed to initiate, which prevented local clearing of the fault at the San Juan SP 115 kV bus.
- Additional issues during the remote backup operations extended the reach of the outage. These issues included remote ends that did not operate, or operated late, and coordination issues in Sabana Llana TC, Aguas Buenas TC, Caguas TC, and Vega Baja TC substations.

The chain of events and each root cause are discussed in this report.

**Corrective Actions**

While addressing the scope of these legacy infrastructure challenges will take time, LUMA is determined to take steps to help improve immediate reliability issues by making the necessary short-term repairs, as well as transforming the resilience of the grid over the long-term by advancing FEMA projects. The short-term and long-term actions are presented below.

**Short-term Actions**

The short-term actions identified to help mitigate the impact of these past legacy issues effect on reliability and improve the grid's resiliency are noted below, and are scheduled to be completed by LUMA before the end of July 2022:

- Implementation of dc monitoring in San Juan SP is underway. Final plan and schedule will be completed the week of 3/21.
- Develop a schedule by the week of 3/14 to implement dc monitoring in the following substations: Viaducto TC, Monacillos TC, Bayamón TC, San Juan SP, Costa Sur, and Sabana Llana TC. These substations were chosen based on weighing parameters, such as: station loading, asset health, age, and single point of failure.
- As the first two contingencies were due to failing aging equipment, the energization of the San Juan SP protection and control system upgrade and the 38 kV gas-insulated switchgear project will be scheduled for assessment. These projects and equipment were constructed more than a decade ago and never placed into service. An assessment plan was completed.
- Continue with functional relay to circuit breaker testing systematically.
- Address the corrective actions as presented in section 5.1.5.
- Collaborate with PREPA on corrective actions resulting from the battery tests at the San Juan SP once received from their contractor.

**Long-term Actions**

Given the scope and nature of legacy operational issues that are found across the energy grid, more long-term actions will be critical to fully reduce the risk of large-scale outages such as the one experienced on February 2nd. These long-term actions will be planned, scheduled, and tracked to completion aligned with LUMA's Long-Term Investment Plan (LTIP) initiatives and include the following:

- As part of LUMA's Area Planning and Substation improvement and expansion plans, the team will continue to analyze capacity, redundancy, and reliability factors affecting the transmission system, electrical substation, or switchyard facility. For instance, substation configuration evaluation from straight bus to ring bus or circuit breaker and a half, and additional transformers for N-1 design compliance.
- Inclusion of transient recorders and certain substations protection systems into the new cyber-secure platform with remote access, including Sabana Llana TC, amongst others.
- Completion of the protection and control system upgrades in Viaducto TC and Monacillos TC.
- Development of a protection and control renovation plan for Bayamón TC in coordination with existing multiple capital projects underway.
- Development of a protection and control upgrade plan to supplement the Substation Rebuild projects currently in progress.
- Continue the transition to new protection relaying philosophies, according to industry standards and best practices, including revised transmission line-zone protection and revised backup protection for lines and transformers. The changes proposed will provide faster response times of backup protection systems and eliminate chances for miscoordination.

While these long-term actions depend on the adequate funding of various FEMA projects, implementing these steps and actions will help ensure fast clearing of the fault and proper operation of substation equipment in addition to isolating the disturbance should a similar event occur.

**Conclusion**

Preventing future large scale outages demands a clear and transparent explanation of the causes that contribute to such events. In the case of the February 21st, 2022 outage, it is clear that past legacy issues continue to pose an ongoing threat to everyday reliability. While service interruptions of this size would be rare in any modern energy system, the fragile and aged nature of the transmission and distribution system in Puerto Rico highlights the significant challenges that still exist.

To help provide the reliability that our customers expect and deserve, LUMA is committed to undertaking all necessary actions, including an area-wide protection study, which began last year, that will help identify broad improvements to the protection systems of the critical transmission infrastructure across Puerto Rico. We understand that any electrical outage, no matter its magnitude or reason, is very frustrating for our customers. And while significant progress has been made since June 1st, the day of transition, it is clear that significant work remains to address these legacy issues. All of us at LUMA remain committed to not only being transparent about the causes of such events, but to building an energy system that our 1.5 million customers can rely on.

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# 1. Introduction

This report is based on the forensic analysis of the system's behavior during the electrical system disturbance that caused a widespread power outage on Monday, February 21, 2022.

Before the event, the electrical system was in the normal operational state. On February 21, 2022, at 13:19, a single phase-to-ground fault occurred on the 115 kV line 38100 from San Juan Steam Plant (SP) to Viaducto Transmission Center (TC), approximately one mile from San Juan SP. The fault was the result of vegetation contacting the line, which was detected by the line relays at both terminals. The circuit breaker at Viaducto TC operated correctly, while the circuit breakers at San Juan SP failed to operate due to lack of direct current (dc) power supply caused by damaged wires.

[redacted] However, the breaker failure scheme at San Juan SP failed to operate (due to aged wiring), requiring all the 115 kV circuits from San Juan SP to operate at the remote end to clear the fault.

Additional issues were identified during the remote backup operations explained in this report. This resulted in subsequent outage events across the power system in Puerto Rico.

The estimated number of customers affected by this outage is near 590,000, or 40.3% of the customer base.

Power was restored to approximately 98% of the affected customers within three hours. At 16:12, the number of customers disconnected was below 19,000, or 1.3% of the customer base.

The report covers the known details of the four stages of the power outage, as described in further detail in Sections 2 and 3 of this report:

- Initial fault at line 38100 – Viaducto TC to San Juan SP.
- Circuit breaker failure event in San Juan SP.
- Unresponsive breaker failure protection in San Juan SP and remote-end operations.
- System-wide disturbance.

The outage events directed Puerto Rico's electrical system through three out of the five-power system operational states as defined by the Electrical Power Research Institute (EPRI):

- Normal state - The electrical system operation is normal.
- Alert state - The electrical system is crossing the security levels for stability but can be restored by the protection scheme quickly.
- Emergency state - Electrical system under a severe disturbance but mostly intact, protection backup contingencies are activated.
- In extremis state - Extreme protection actions, like load shed and special operational maneuvers, by the Control Center personnel are taken to avoid a blackout.
- Restoration state - The electrical system returns to normal conditions.

# 2. Stages of the Disturbance

## 2.1 Stage One: Initial Fault

A short circuit in line 38100 has been identified as the initiating event of this power outage. This event is defined as the first contingency or N-1 (n minus one).

At 13:19, a phase-to-ground fault initiated within a mile from San Juan SP, evolving into a three-phase fault. A second later, the fault evolved to line 38400 Viaducto TC – San Juan SP. Lines 38100 and 38400 share the support structure in this location.

[redacted]

**Figure 2-1 115 kV and 230 kV Lines in the Metro Area - Faulted Line 38100 Highlighted**

The initial fault was recorded by the line relay in Viaducto TC. The distance to the fault was calculated using the relay's data and was validated by the Field-operations team.

In addition, the security cameras of a local business near the fault recorded the probable fault on video. A cell phone recording after the fault shows a small brush fire was initiated by the short circuit.

**Figure 2-2 Fault Initiation due to Vegetation Reported by Line Patrol (Note Line Proximity to Vegetation)**

The coordinates of the video location are [redacted]. This area is accessible and beside line 38100/38400's right-of-way. LUMA's personnel completed an on-site investigation. The distance to the fault has been determined to be [redacted], matching the calculated value.

Reports point to a flashover from the line to vegetation under the line.

Line 38100's fault was detected by the line-differential relay, model SEL-311L, at Viaducto TC and circuit breaker 38190 opened in six cycles (100 ms).

Line 38400's fault was detected and cleared properly at both ends. Line 38400's fault occurred one second after the original fault due to flashover from line 38100.

## 2.2 Stage Two: Failed Circuit Breaker Operation at San Juan SP

[redacted] The circuit breakers 38140 and 0084 did not trip, resulting in a sustained fault in line 38100. This is defined as the second contingency or N-2 (n minus two). At this stage, the system enters the alert state.

The cause of the circuit breakers not operating was the lack of dc power to the circuit breakers, due to a tripped dc circuit breaker. The dc circuit that was tripped is the power supply for the three circuit breakers in the bay: 38140, 0084, and 0086.

After field troubleshooting, a short circuit in the dc wiring, due to degraded insulation by aging, was located, and the corresponding dc circuit breaker tripped.

**Figure 2-3 Short Circuit in DC Wiring due to Degraded Insulation (Circled)**

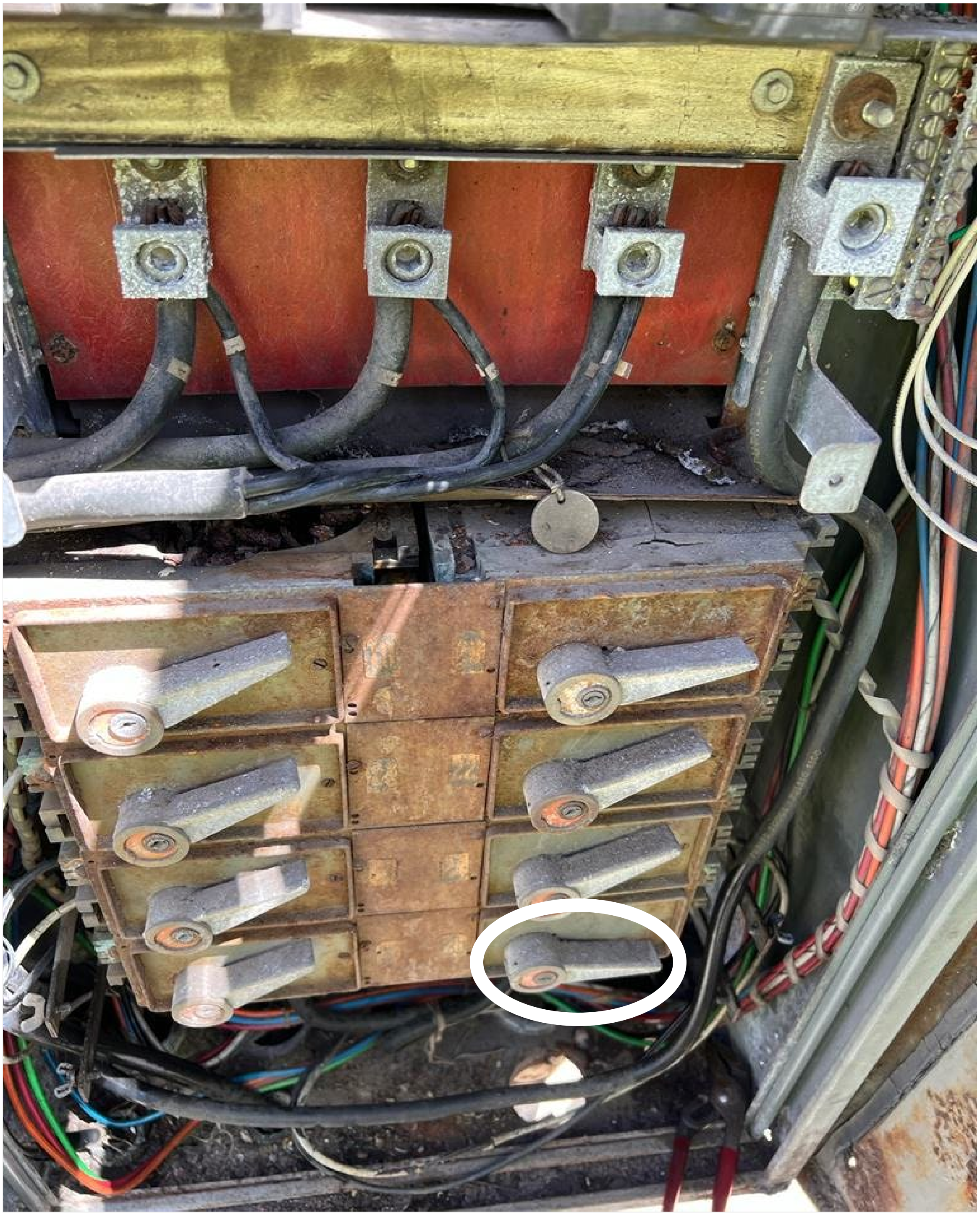

**Figure 2-4 Weathered and Rusted DC Circuit Breaker Panel for 115 kV Circuit Breakers' Power; Bottom Right Circuit Breaker Tripped (Circled)**

## 2.3 Stage Three: Unresponsive Breaker Failure Protection at San Juan SP

Following the failed operation of the circuit breakers, the Breaker Failure Protection function (BF) implemented in San Juan was expected to operate. This function opens all the sources on the 115 kV bus.

However, the BF scheme did not operate due to faulted current transformer (CT) wiring, preventing the BF relays to read the system currents. At this stage, the system enters the emergency state.

Figure 2-5 presents a series of images illustrating the CT wiring issues identified in San Juan SP.

Exposed wire, which in today's standards should be protected by running inside a conduit or trench rather than being buried. Trash adjacent.

Wire that failed circled. Note exposure to elements and trash adjacent.

Excavated cable reveals cable insulation deterioration.

Closeup of wire's damaged insulation.

Another example of wire insulation damage and trash on jobsite

**Figure 2-5 Multiple CT Wiring Issues Identified in San Juan SP**

## 2.4 Stage Four: System-Wide Disturbance

With a sustained fault on line 38100, and no local clearing at San Juan SP, remote backup protection started clearing the sources to the fault at their remote ends.

These remote-end operations are defined as the third contingencies or N-3 (n minus three).

The sudden loss of multiple 115 kV lines, along with the losses of the San Juan SP Generators #6 and #9 and the Palo Seco Generator #3, created system instability in the Metro area.

The system's frequency escalated to 61.61 Hz and remained in the alarmed state for approximately 20 minutes before reaching normal state.

During the N-3 stage, several remote terminals did not operate as expected, and other circuit breakers operated unexpectedly. These maloperations and mis-coordinated operations added to the extent of the outage, which reached the following points:

- To the west: Vega Alta in the 38 kV system and Vega Baja in the 115 kV system.
- To the East: Daguao in the 38 kV system and Fajardo in the 115 kV system.
- In addition, the disconnection of the two 230/115 kV transformers in Bayamón TC and Sabana Llana TC prevented the flow of generation from the south to the Metro region.
- Furthermore, Aguirre Generation Unit #2 tripped offline at 13:22.

The undesired operations include:

- Expected remote trip of line 38700 from San Juan SP to Palo Seco SP did not occur.
- Remote trip in line 38500 occurred later than expected.
- Unexpected trip of Sabana Llana 230/115 kV transformer.
- Unexpected trip of line 39000 at Aguas Buenas.
- Unexpected trip of line 37800 at Caguas.
- Unexpected trip of line 37400 Vega Baja – Dorado.

# 3. Timeline and Analysis of Operations

The following diagram details the operations of the outage event. The operations have been grouped by their contingency level.

[redacted]

**Figure 3-1 Fault on Line 38100 Highlighted in Yellow**

[redacted]

**Figure 3-2 Disturbance Timeline**

**Table 1 Event List**

[redacted]

## 3.1 Initial Fault in Line 38100 (N-1 Event)

The initial fault occurred on line 38100 between San Juan SP and Viaducto TC. The fault started as a B phase to ground fault that evolved after 75 ms into a B phase to C phase to ground fault. The line is protected by a redundant line-differential scheme provided by a pair of SEL-311L relays and a pair of SEL-387L relays.

SCADA showed that the trip signals from the differential and backup protection were asserted as follows: 87-1 trip = 34.62 cycles, backup (BU) trip = 22.38 cycles, and BU2 trip = 30.36 cycles. Circuit breaker 38140-0084 did not open, and the breaker failure scheme failed.

[redacted]

**Figure 3-3 SCADA SOE Asserted Times for Relay Trips Indicating a Breaker Failure Initiate**

The review of the relay records from the Viaducto side confirms that the relay issued a trip command 16 ms after the fault started. The circuit breaker interrupted the fault current 112 ms after the trip was issued.

The figure below shows the fault current and fault voltages recorded on the Viaducto terminal and the relay pickup and trip commands.

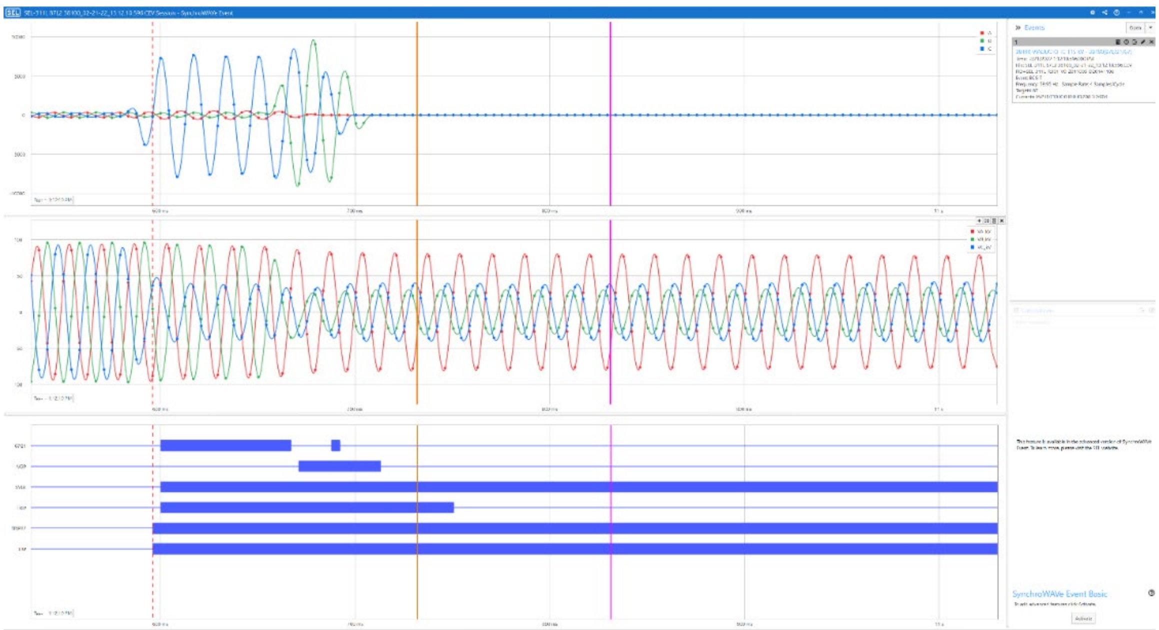

**Figure 3-4 Fault Records Data from Viaducto Terminal**

No relay records are available for the line 38100 from the San Juan terminal. However, the differential relay SEL-311L and the SEL-387L records typically record the local and the remote-terminal fault currents. Therefore, the records from the Viaducto terminal provided the current records from the remote terminal (San Juan) that were used for the analysis in this report.

The figure below presents the current at the San Juan terminal. It is visible that the current is not interrupted until the record stops. It can be assumed, and is shown in the SCADA record, that the San Juan relay issued a line-differential relay trip around the same time as the Viaducto terminal. The trip was issued, based on the available data, at least for 430 ms. The trip time was sufficient to trip the circuit breakers 38140 and 0084 at the San Juan terminal to clear the fault, and to issue a circuit breaker failure trip for the contingency that one or both circuit breakers could not operate.

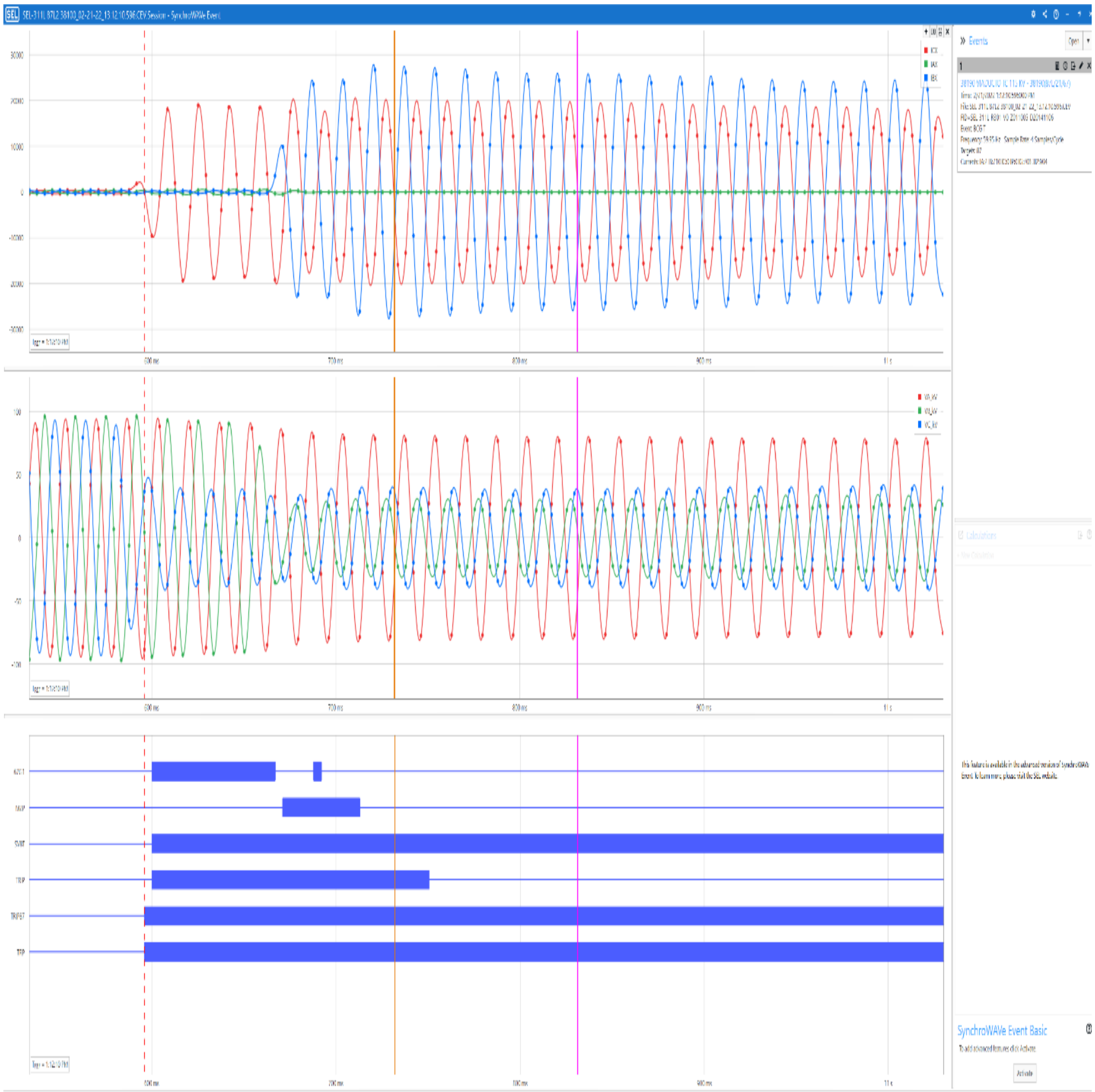

**Figure 3-5 Fault Records Data from Viaducto Terminal (Showing San Juan Fault Currents)**

Inspection showed that the dc power supply of the 38140, 0084, and 0086 high-voltage circuit breakers was tripped. Without dc power, the circuit breakers were unable to operate.

The next step to clear the fault in this scenario is to issue a breaker failure protection trip to clear all surrounding circuit breakers of circuit breakers 38140 and 0084 to isolate the fault. This did not happen.

## 3.2 Unresponsive Breaker Failure Protection (N-2 Events)

As described in the previous section, the tripped power supply for circuit breakers 38140 and 0084 did not allow the fault clearing of the fault on line 38100 with the circuit breakers responsible to clear the fault. The scheme used by LUMA would monitor the circuit breaker's currents and issue a breaker failure trip, after a delay time, to all surrounding circuit breakers to clear the fault.

The breaker failure relay used for this purpose is an electromechanical relay type CHC overcurrent relay in combination with a timer relay model TD-5 and supervised by the primary relay trip.

Breaker failure scheme relays are connected to the metering CTs (see table below).

**Table 2 Breaker Failure Scheme Relays Connected to Metering CTs**

| *CURRENT TRANSFORMER* 38140 | | | | *CURRENT TRANSFORMER* 0084 | | | |
|---|---|---|---|---|---|---|---|
| *POSITION* | *TYPE* | *RATIOS* | *USE* | *POSITION* | *TYPE* | *RATIOS* | *USE* |
| 135X | BCM | 80-160-60-100 | METERING | 135X | BCM | 80-160-60-100 | UNIT DIFF. |
| 135Y | BCM | 80-160-60-100 | BUS DIFF. | 135Y | BCM | 80-160-60-100 | MET-F.DET. |
| 246X | BCM | 80-160-60-100 | SEC.PROT. | 246X | BCM | 80-160-60-100 | PRI.PROT. |
| 246Y | BCM | 80-160-60-100 | PRI.PROT. | 246Y | BCM | 80-160-60-100 | SEC.PROT. |

The breaker failure (BF) scheme did not, however, operate due to faulted current transformer wiring, preventing the BF relays to read the system currents.

The rest of the BF scheme was tested after the event and is working properly. The test was repeated with dc power off in circuit breakers 38140, 0084, and 0086. In each case, the BF scheme operated properly, and it was determined that the lack of dc power in circuit breakers 38140, 0064, and 0086 did not affect the relays' scheme.

The battery systems in San Juan SP feeding the switchyards belong to PREPA. PREPA has provided a record of their monthly inspections and informed of battery tests already contracted. The reports on the San Juan SP tests are not available at this moment.

After the circuit breakers failed to operate, and the breaker failure protection for these circuit breakers also did not operate, the fault needed to be cleared by all remote backup line relays.

## 3.3 San Juan SP Remote Line Terminals; Correct Operations (N-3 Events)

### 3.3.1 Line 38400 (Parallel to 38100) fault and Viaducto to San Juan Operation

The line that runs parallel to the 38100 line on which the fault started was tripped during the event. There are no records available to show when the circuit breaker 38490 on the Viaducto side of the line 38400 tripped.

It is evident, based on records from the San Juan side, that the line was in service and carried load current when the fault on line 38100 started, but it was already tripped in Viaducto 1.7 seconds later when the San Juan terminal on the line tripped. Based on the fault current measured in the record that was triggered when the fault on line 38100 started, the Viaducto terminal should have measured a current in phase B of about 1,520 A and a current of 1,280 A in phase C during the fault duration. For the evaluation, when the 51P element at the Viaducto side could have operated, the phase current of 1,520 A was assumed. The settings relevant for the 51P element are shown below:

CTR = 400 51PP = 2.00 51PC = U1 51PTD = 1.50

Based on this data, an anticipated tripping time of 1.24 seconds is calculated. However, there are no records of Viaducto tripping at this time, despite the circuit breaker having been tripped at some time before the subsequent fault on 38400.

Zone 3 has a two-second time delay and was therefore not involved in the operation.

The San Juan line side was tripped based on a ground fault that may be the result of an evolving fault caused by smoke or an arcing of the initial fault on line 38100 approximately 1.7 seconds after the initial fault started. The time was calculated based on two relay records from the San Juan line terminal of line 38400. The first record showed the start of the initial fault on line 38100 (see Figure 3-6) and was triggered by a Zone 2 pickup of a distance element. The second fault record (see Figure 3-7) was in response to a ground fault on line 38400. The second record also documents that the remote end must have been open at this time as no load current is visible.

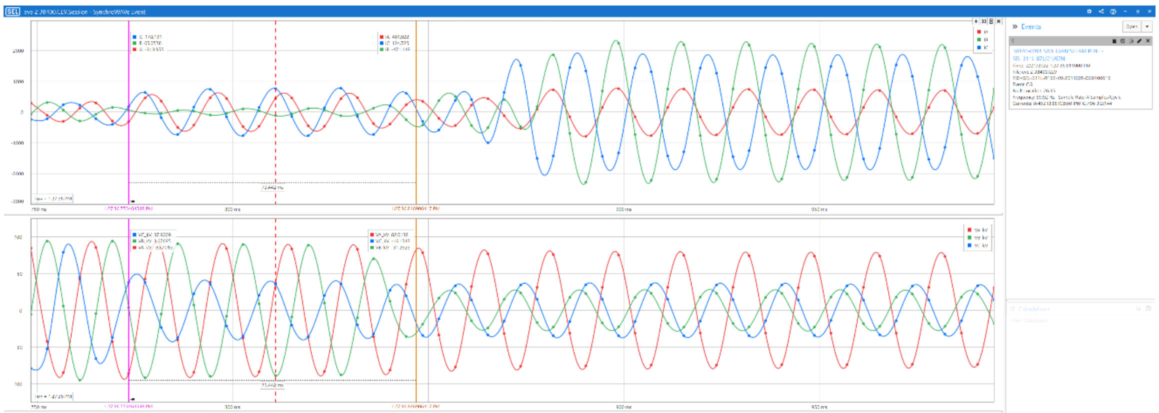

**Figure 3-6 Fault Records Data from San Juan Terminal of Line 38400 - Initial Fault on 38100**

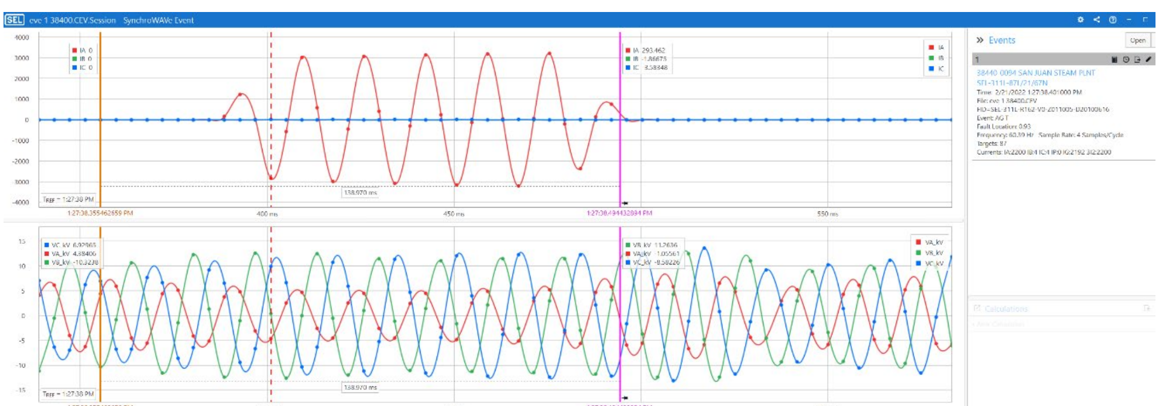

**Figure 3-7 Fault Records Data from San Juan Terminal of Line 38400 - Evolving Fault on 38400**

### 3.3.2 Line 38300 Monacillos to San Juan Operation

The correct operation from the protection located on the Monacillos terminal for line 38300 is documented by two records for relay SEL-311L. The first record recorded the start of the fault on line 38100 and provided a time reference for the internal relay time (see Figure 3-8). The fault start was time-stamped with a time of 1:17:45.472 P.M. based on the internal relay time. The second record documented the fault clearing by a 51P element after about 1.2 seconds (see Figure 3-9). The opening of the circuit breaker has a timestamp of 1:17:46.716 P.M. based on the internal relay time. Based on the two timestamps, the fault clearing can be calculated to 1.244 seconds.

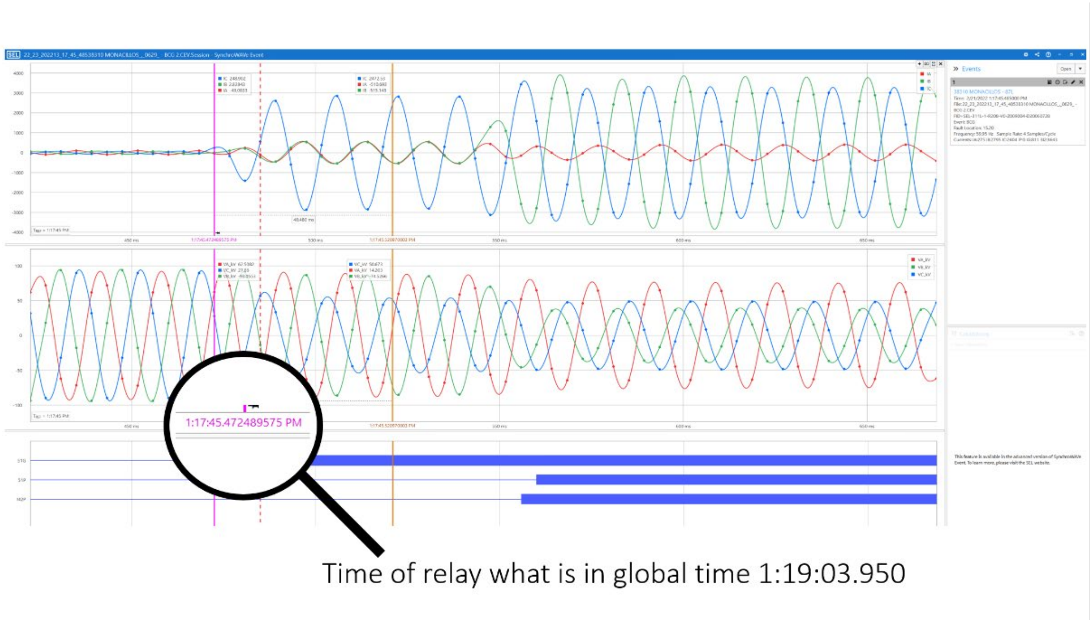


**Figure 3-8 Fault Records Data from Monacillos Terminal of Line 38300 (Relay SEL-311L)**

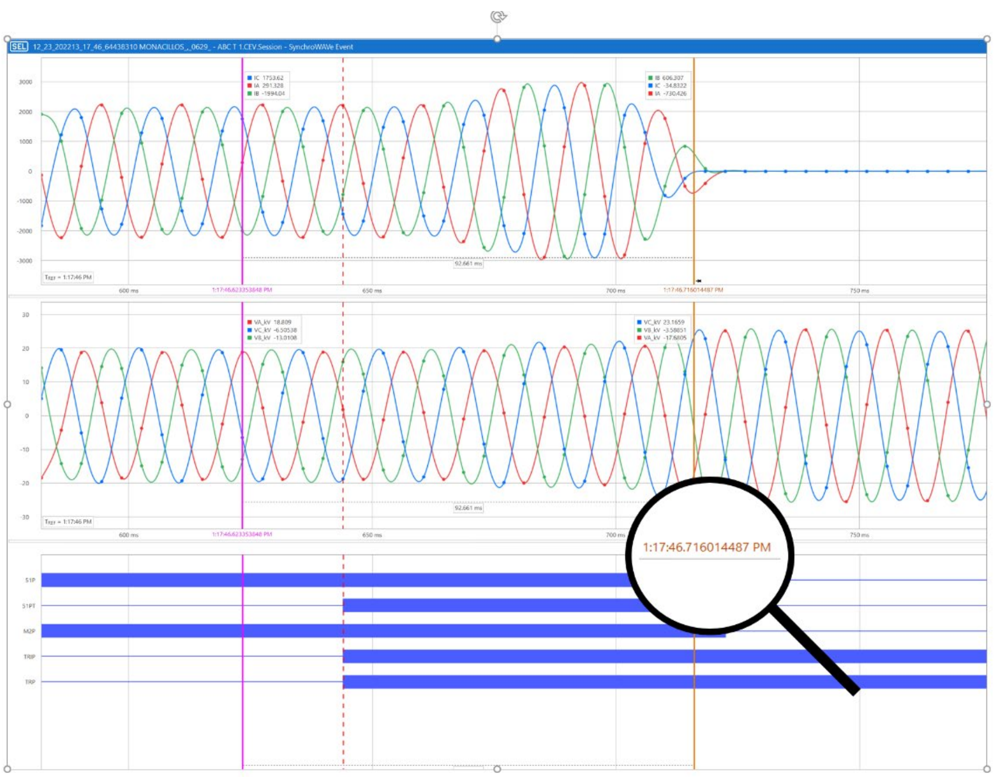


**Figure 3-9 Fault Records Data from Monacillos Terminal of Line 38300 (Relay SEL-311L)**

### 3.3.3 Line 38600 Bayamón to San Juan Operation (38630-0092)

The San Juan SP to Bayamón TC Line 38600 remote terminal circuit breaker tripped in Bayamón TC.

At 13:19:05.15, the remote terminal at Bayamón to San Juan tripped, 1.19 seconds after the fault at line 38100 from San Juan to Viaducto initiated. It was shown in the transient recorder and relay records that the fault changed from C-G to C-B and finally A-B-C. Short-circuit currents observed were $I_a$ = 300 A, $I_b$ = 3,056 A, $I_c$ = 2,339 A. The relay tripped with $I_a$ = 2,524 A, $I_b$ = 2,634 A, $I_c$ = 2,539 A.

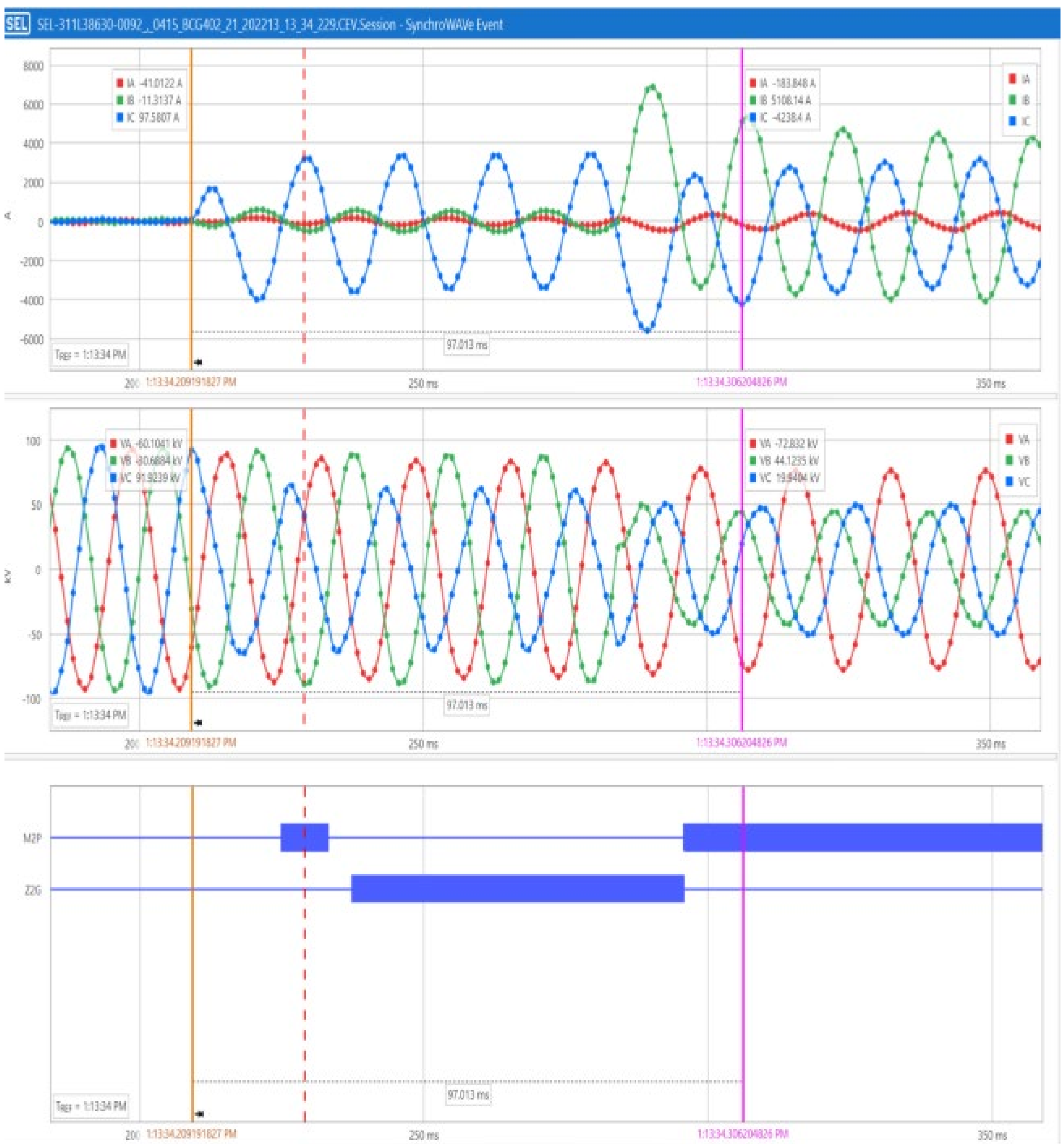


**Figure 3-10 Fault Records Data at Line 31800 Initiation Sensed by 38630-0092 at Bayamón**


**Figure 3-11 Fault Records Data for Line 38600 trip at Bayamón**

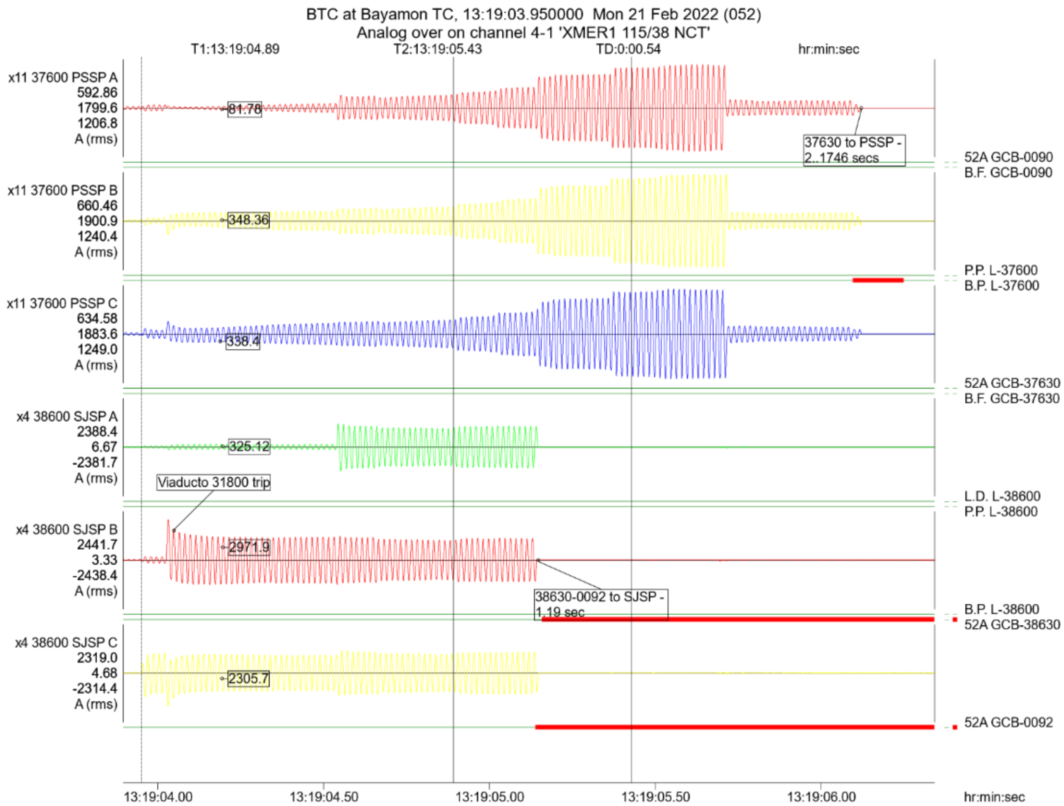


**Figure 3-12 Transient Recorder Fault Records Data for Line 38600**

## 3.3.4 Line 40400 from Hato Rey to San Juan Operation

Line 40400's remote end did not operate.

Initial findings point to a correct operation due to other system operations, where the sources contributing to the fault from this line were disconnected before the line had the chance to trip.

It is recommended to confirm the timeline of the event against the system model to confirm this operation.

## 3.3.5 San Juan Generation Unit #6 Operation

As per the report received from PREPA, Unit #6 was generating 160 MW prior to the event.

During the disturbance, the gas turbine's revolutions reached 3,735.883 r/min, and the steam turbine's revolutions reached 3,796.587 (13:19:06:358). The generation unit had a sudden load loss and tripped.

The generator protection activated Lockout 86-1 with a phase overcurrent 51V alarm.

Note that the times reported are different than the times recorded in LUMA's SCADA due to different time sources.

The speed reported for this unit corresponds to a frequency of 62.2647 Hz, which is equal to the frequency recorded by the transient recorders.

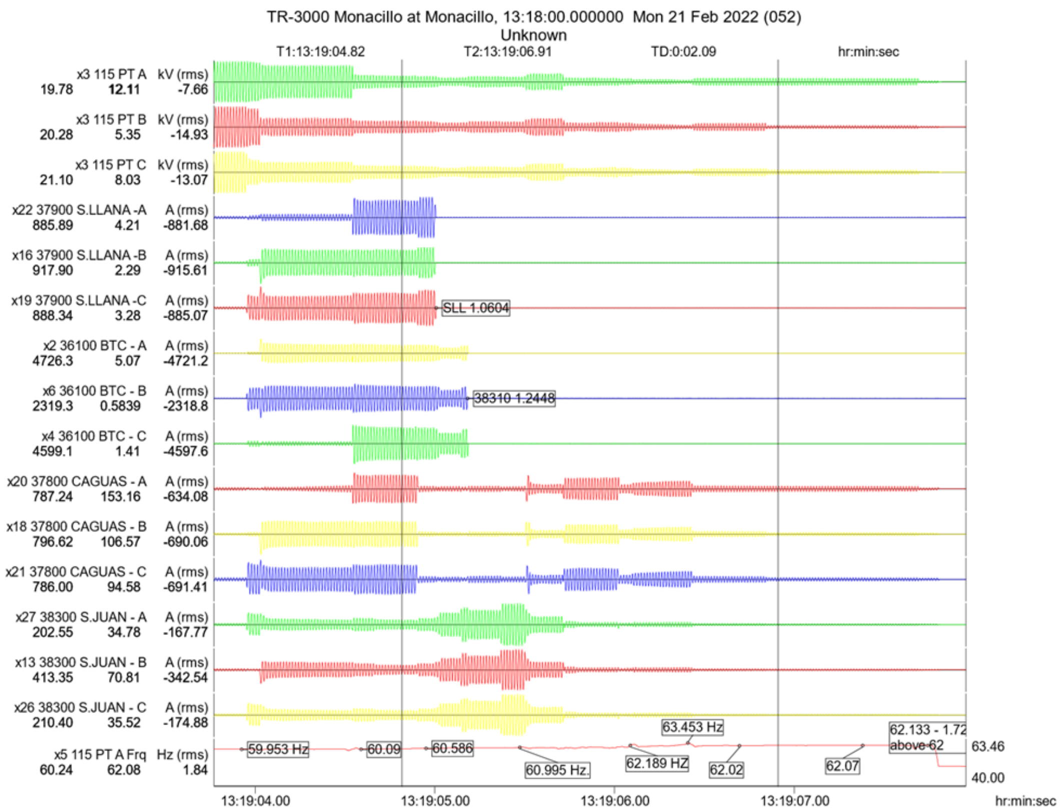


**Figure 3-13 Frequency Response During the Event**

### 3.3.6 San Juan Generation Unit #9 Operation

As per the report received from PREPA, Unit #9 was generating 66 MW prior to the event.

During the disturbance, the steam turbine reached 3,729 (13:19:04:338) r/min. The generation unit had a sudden load loss, tripping at 13:19:09:781.

The generator protection activated Lockout Generator with a Low Lube Oil Pressure Trip alarm in Mark VI.

Note that the times reported are different that the times recorded in LUMA's SCADA due to the different time sources.

SCADA registered a generator trip 1.95 seconds after the fault at line 38100 initiated.

The speed reported for this unit corresponds to a frequency of 62.15 Hz, which is equal to the frequency recorded by the transient recorders.

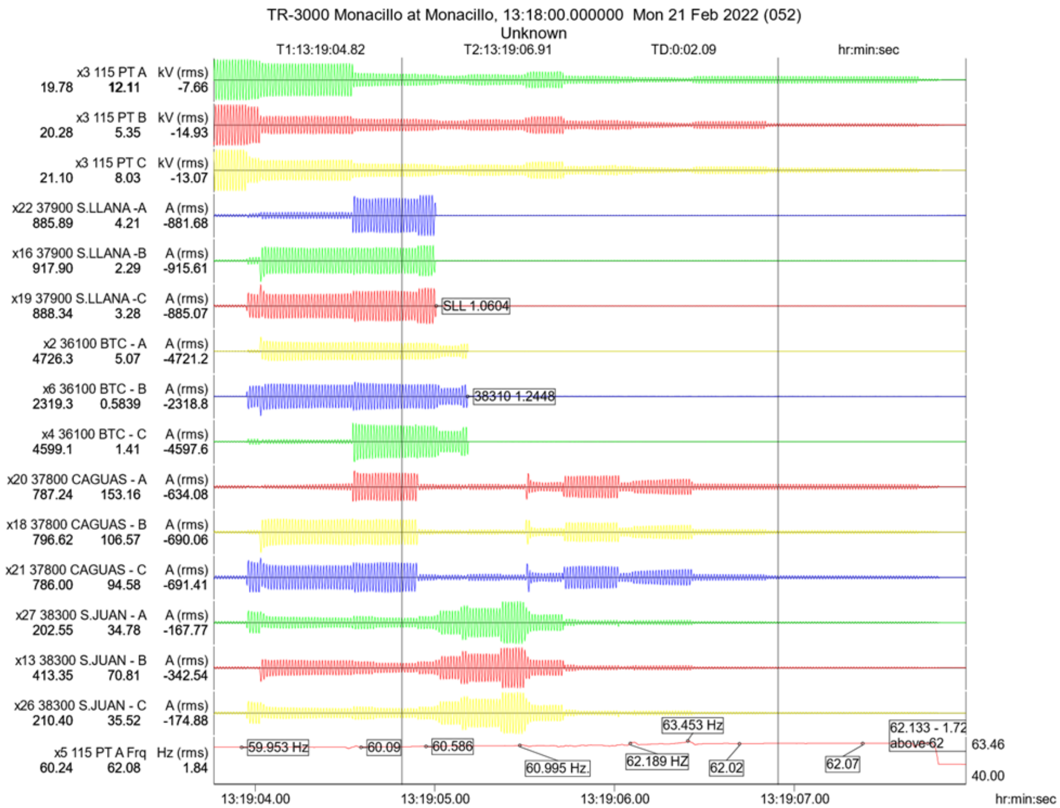


**Figure 3-14 Frequency Response During the Event at Line 38100**

### 3.3.7 Trip of 115 kV/38 kV Transformer in San Juan

The 115/38kV transformer circuit breakers did not operate.

The Substation Maintenance team completed testing of the protective relay schemes. No issues were reported.

The 38 kV bus in San Juan SP had line 8200 open before the fault. Line 3500 operates normally open at Caparra, therefore the only source available was line 4300 that ultimately is Bayamón. It is plausible that the 38 kV did not have enough contribution for a relay pickup, and the non-operation is correct. Bayamón's terminal, circuit breakers 4340-0020, to Caparra – San Juan opened 2.12 seconds after the fault at line 38100 initiated.

## 3.4 San Juan SP Remote Line Terminals; Incorrect Operations (N-3 Events)

### 3.4.1 Line 38700 Palo Seco to San Juan Operation

Circuit breakers 38720-0090 at Palo Seco S.P. to San Juan Steam Plant did not trip as remote backup protection to the fault at line 38100 from San Juan to Viaducto. From the relay data, the torque-controlled Zone 2 (M2P) time-overcurrent protection (51P) at line 38700 was activated. At 1:19:05.71 (relay time), the 51P and M2P signals deactivated, resetting the time-overcurrent unit. This situation and other circumstances caused the remote-backup trip from the Bayamón terminal to Palo Seco.

The event was sent to the relay manufacturer for further investigation as the relay lost the 51P and M2P signals approximately 1.77 seconds after the fault at line 38100 started corresponding to the time the 230/115 kV transformer at Bayamón tripped.

The coordination check table below lists the tripping in 2.3 seconds with the original currents (see relay event below). Nevertheless, the current did double for 35 cycles, which should have the relay tripping in less time. The expected trip time when the current doubled was approximately 44 cycles. This relay should have tripped if the M2P and 51P signals did not reset.

**Table 3 Expected Trip Times for 38720-0090 During the Fault at Line 38100**

| I. Relay trip time check: | | | Fault at: | San Juan 38100 | | 115000 V. | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Phase current at different fault stages | | | | | | | | Multiple | | | Expected trip time /stage | | |
| Location | Iinitial | Iall feed | Ixtrip | C.T. | Relay | Curve | Tap | T.L. | Init. | All | Xtrip | Tinitial | Tall | Txtrip |
| 38720-0090 | 2200.0 A. | 4100.0 A. | 1400.0 A. | 400/1 | SEL-311L | U3 | 2.4 | 2.33 | 2.29 | 4.27 | 1.46 | 141.0~ | 44.9~ | 494.9~ |

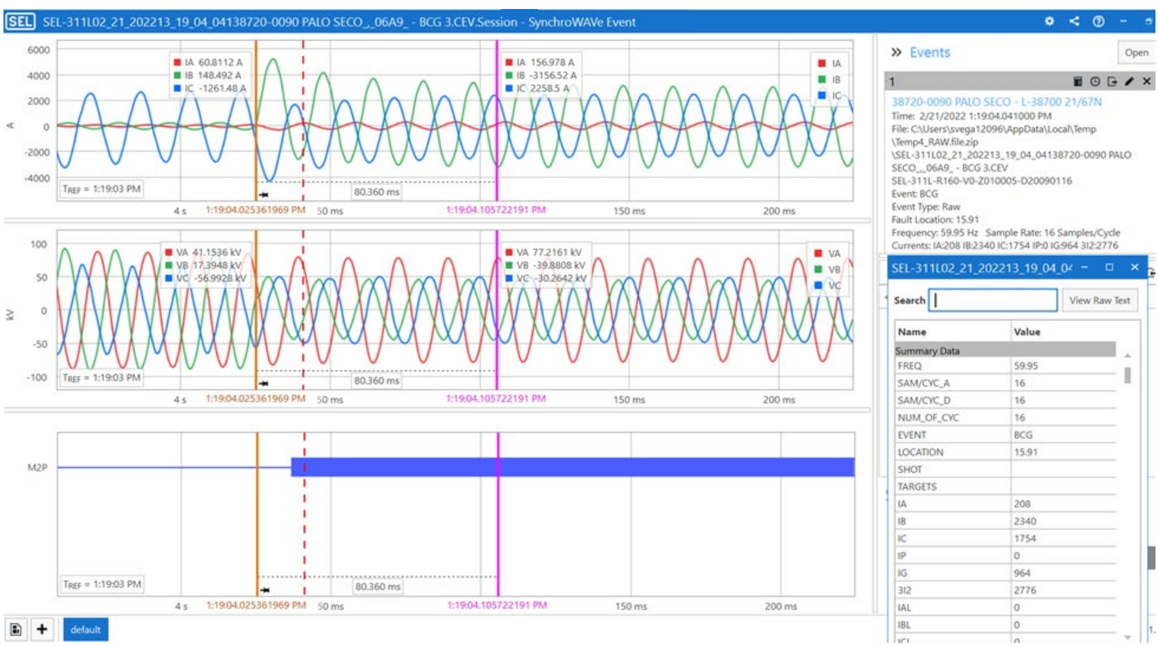


**Figure 3-15 Fault Initiation at Recorded by 38720-0090 Protection at Palo Seco**

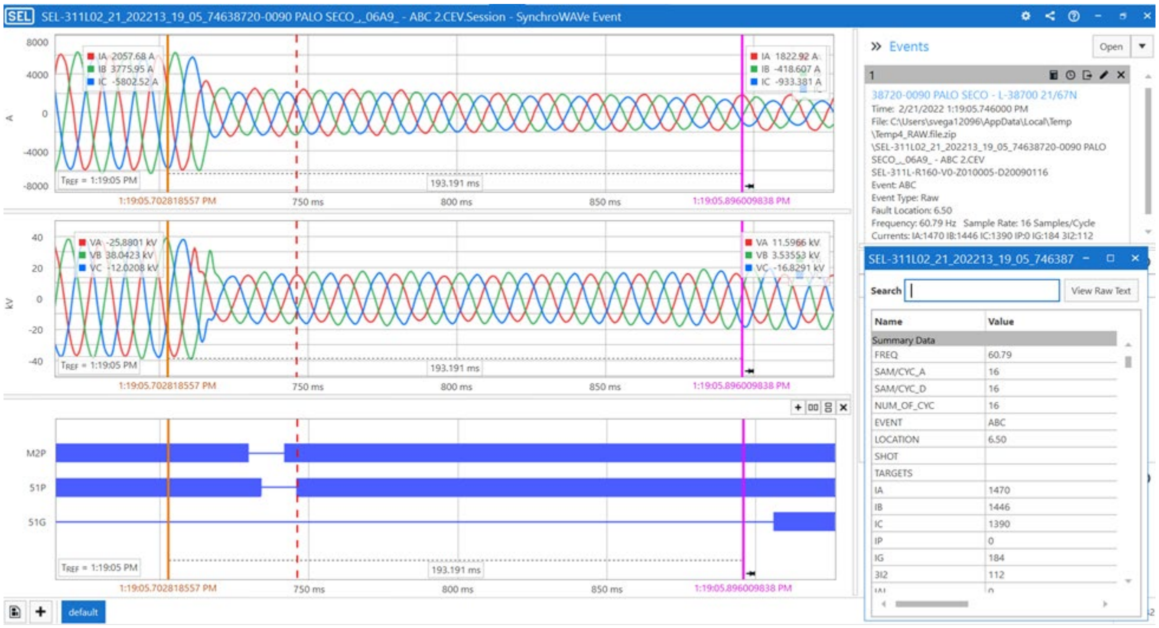


**Figure 3-16 Fault Records Data**

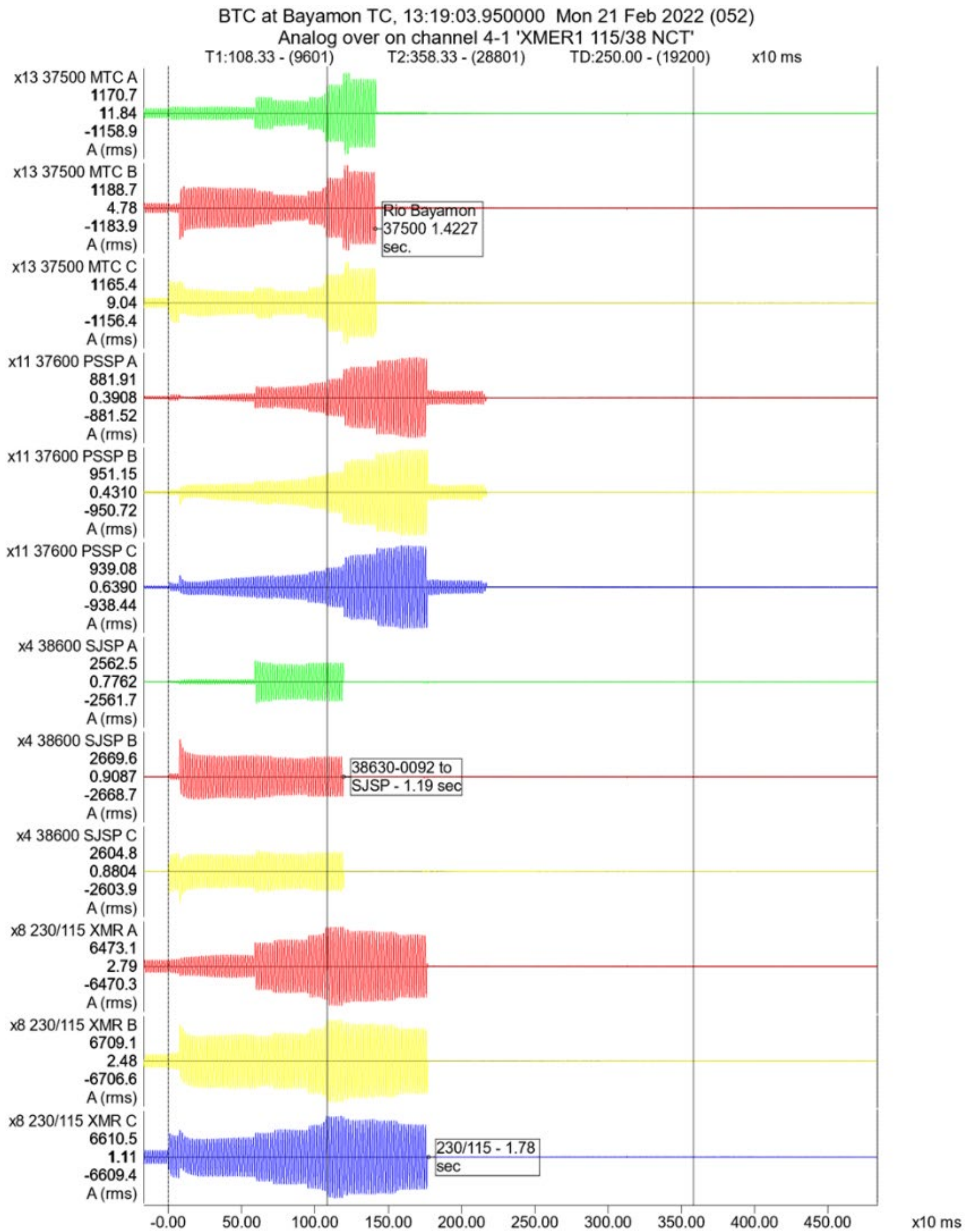


**Figure 3-17 Fault Records Data**

### 3.4.2 Line 38500 to Hato Rey to San Juan Operation

The remote fault clearing from the Hato Rey line terminal on line 38500 is reported in the fault records around 1.55 seconds after the fault's initiation. However, the primary protection relay SEL-311L, installed on this line, correctly issued a 51PT trip signal 1.1 seconds after fault initiation but that did not open the circuit breaker 50 as the fault current was not interrupted (see figure below).

The circuit breaker's operation was tested with no issues reported. Maintenance will be performed in circuit breaker 38550.

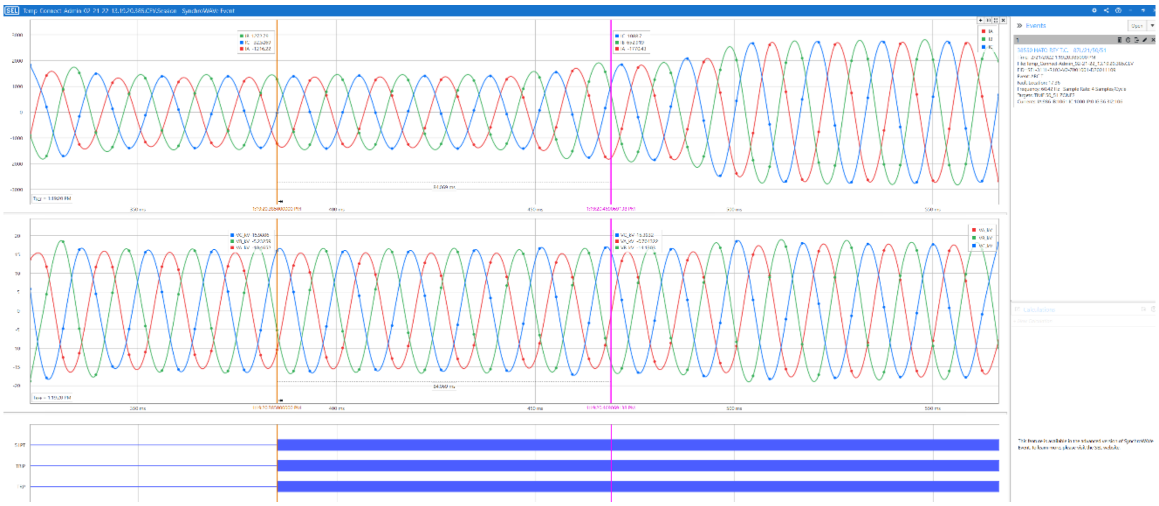

**Figure 3-18 Fault Records Data from Hato Rey Terminal of Line 38500 – No Interruption of Fault Current**

The record from the fault recorder in Hato Rey showed a backup protection operation 1.5 seconds after fault inception, which would be consistent with a Zone 2 operation. The fault current was interrupted based on this backup protection operation 1.55 seconds after fault inception.

## 3.5 Other Events – Undesired Operations

The following trips are undesired operations. The exiting protection schemes require urgent revision.

### 3.5.1 Sabana Llana 230/115 kV Transformer Operation

In Sabana Llana substation, only one of the two 230 kV/115 kV transformers was in service. The transformer in service (T1) is equipped with a backup SEL-321 relay on the 115 kV side. The fault record from the SEL-321 recorded the fault clearing and fault currents (see figure below).

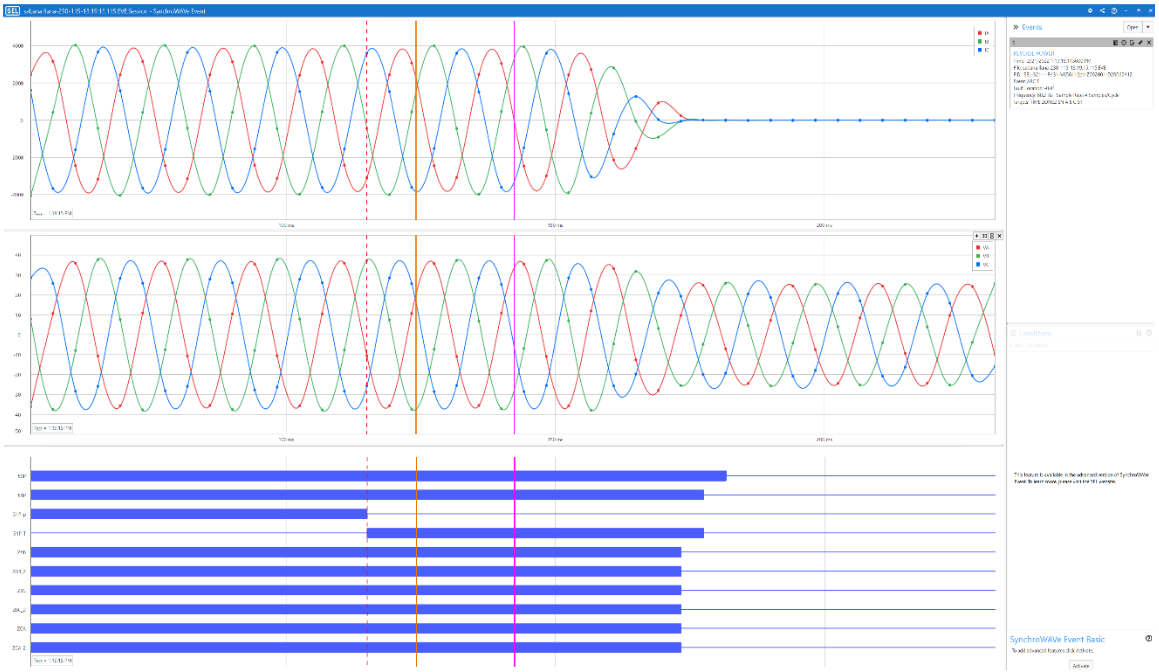

**Figure 3-19 Fault Records Data**

In the recorded data, it is shown that the backup protection element 51P tripped based on the measured fault currents. To calculate the tripping time in relation to the start of the fault, the fault current measured when the relay issued the trip command was used. The fault current may have varied during the event that needs to be considered as an error source for the calculated time.

The fault current in the records showed an amplitude of approximately 2,850 A (prim) that results by a CT ratio of 600 to a secondary current of 4.7 A (seconds). The calculated operating time based on the 51P settings would be approximately 0.93 seconds:

51PP = 2.00 51PC = U1 51PTD = 1.50

This protection setting is miscoordinated with line 38300 Monacillos – San Juan, which should have removed the fault current for the transformer. In addition, it is also miscoordinated with 37900 Sabana Llana – Monacillos that should have tripped when 38300 was slow to operate.

### 3.5.2 Line 39000 from Aguas Buenas to Monacillos (39014-0012) Operation

At 13:19:04.973, circuit breakers 39014-0012 at Aguas Buenas to Monacillos tripped. The Aguas Buenas transient recorder shows that the line tripped 1.0695 seconds after the fault at line 38100 began. Initial $I_c$= 1,328.8 A. As the fault evolved, $I_b$=1,763.1 A, $I_c$=1,235 A. Finally, the protection tripped with $I_a$=1,864 A, $I_b$=2,048 A, and $I_c$=1,942 A.

At 13:19:15:14, ten seconds after line 39100 from Aguas Buenas to Monacillos tripped, circuit breaker 0020 reclosed (in five cycles) to a three-phase fault still present in the system. $I_a$= 2,718 A, $I_b$=2,999 A, and $I_c$=3,132 A.

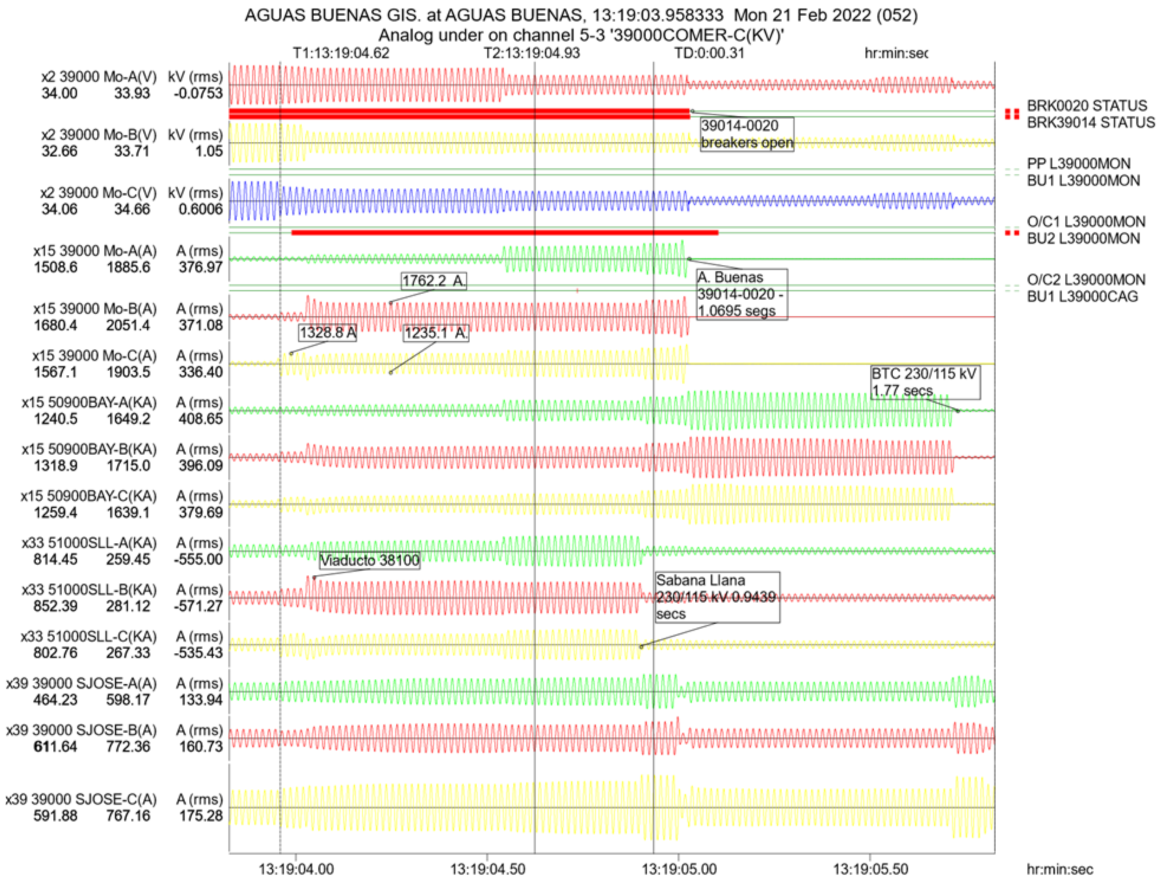


**Figure 3-20 Line 39000 from Aguas Buenas to Monacillos Trip**

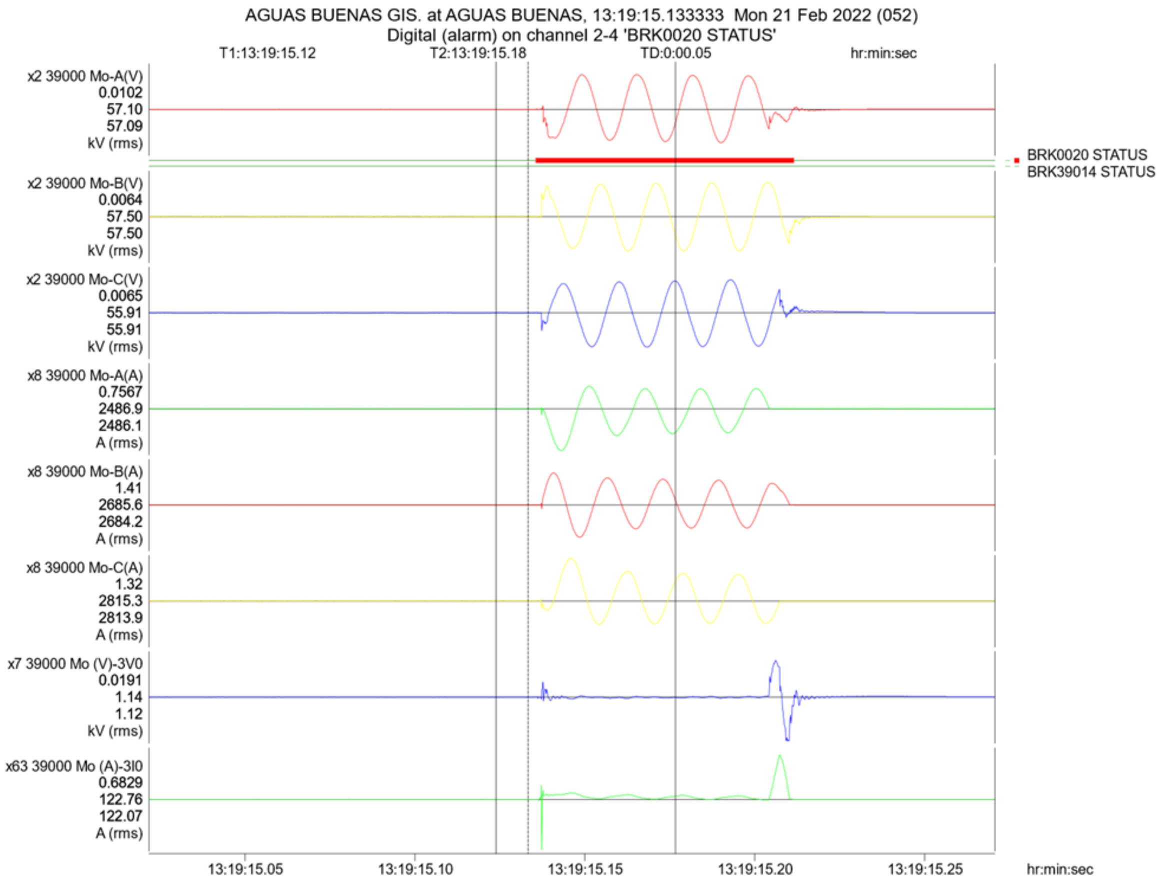


**Figure 3-21 Line 39000 from Aguas Buenas to Monacillos Reclose**

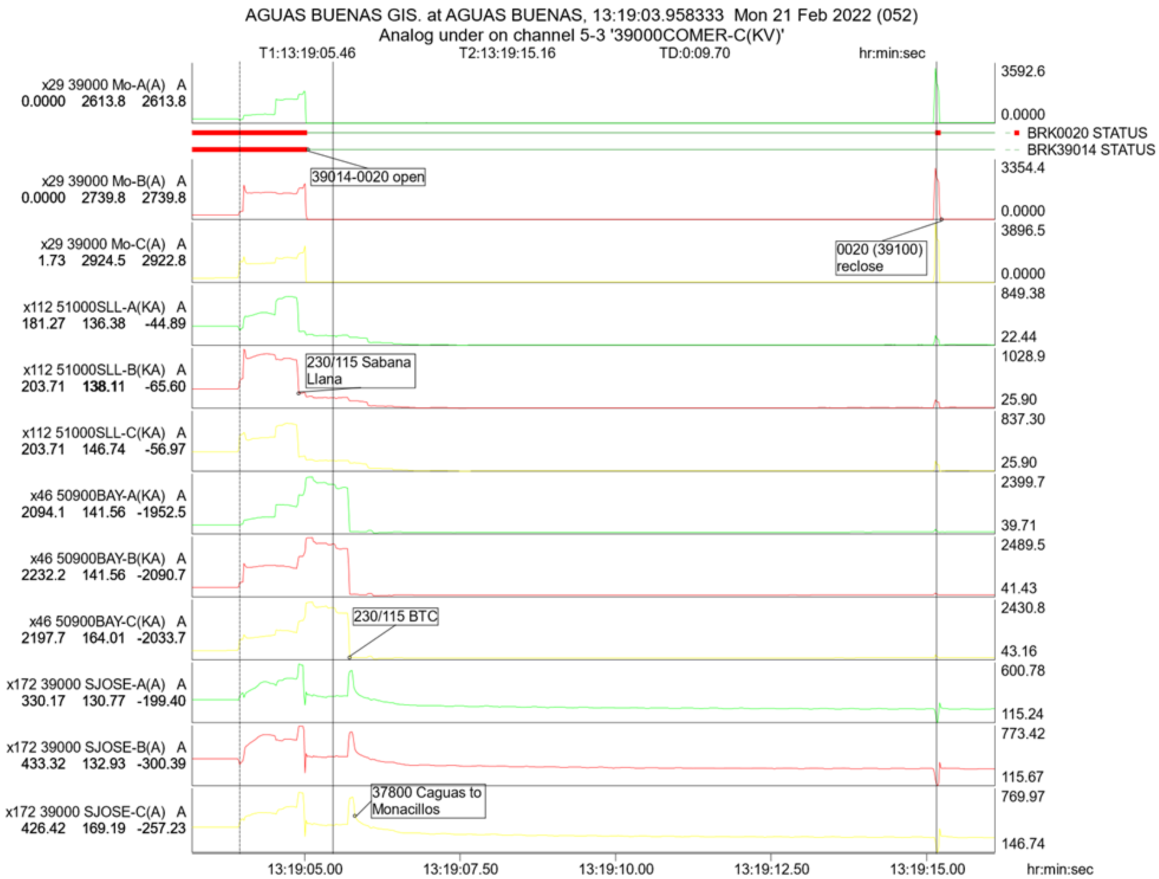


**Figure 3-22 Aguas Buenas Record of line 38100 Fault Event and Line 39000 Reclose**

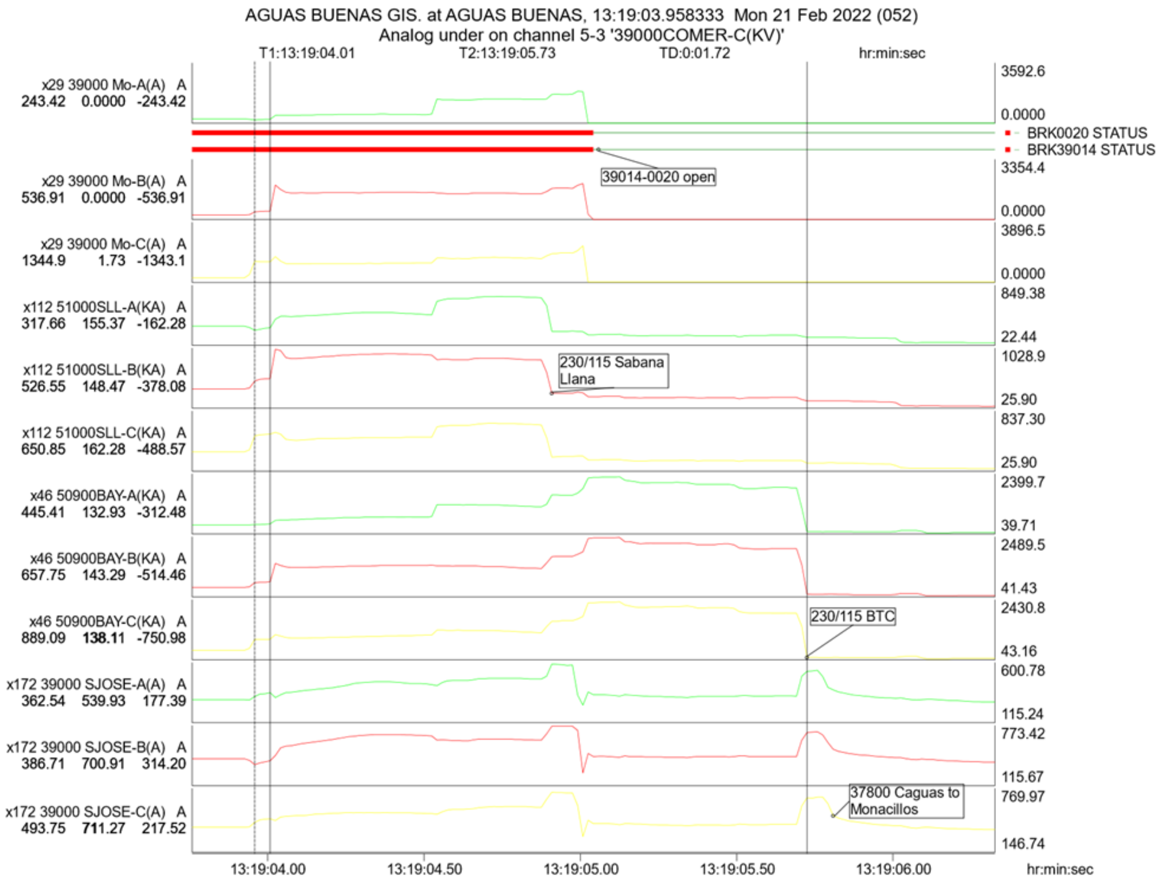


**Figure 3-23 Fault Records Data Detail**

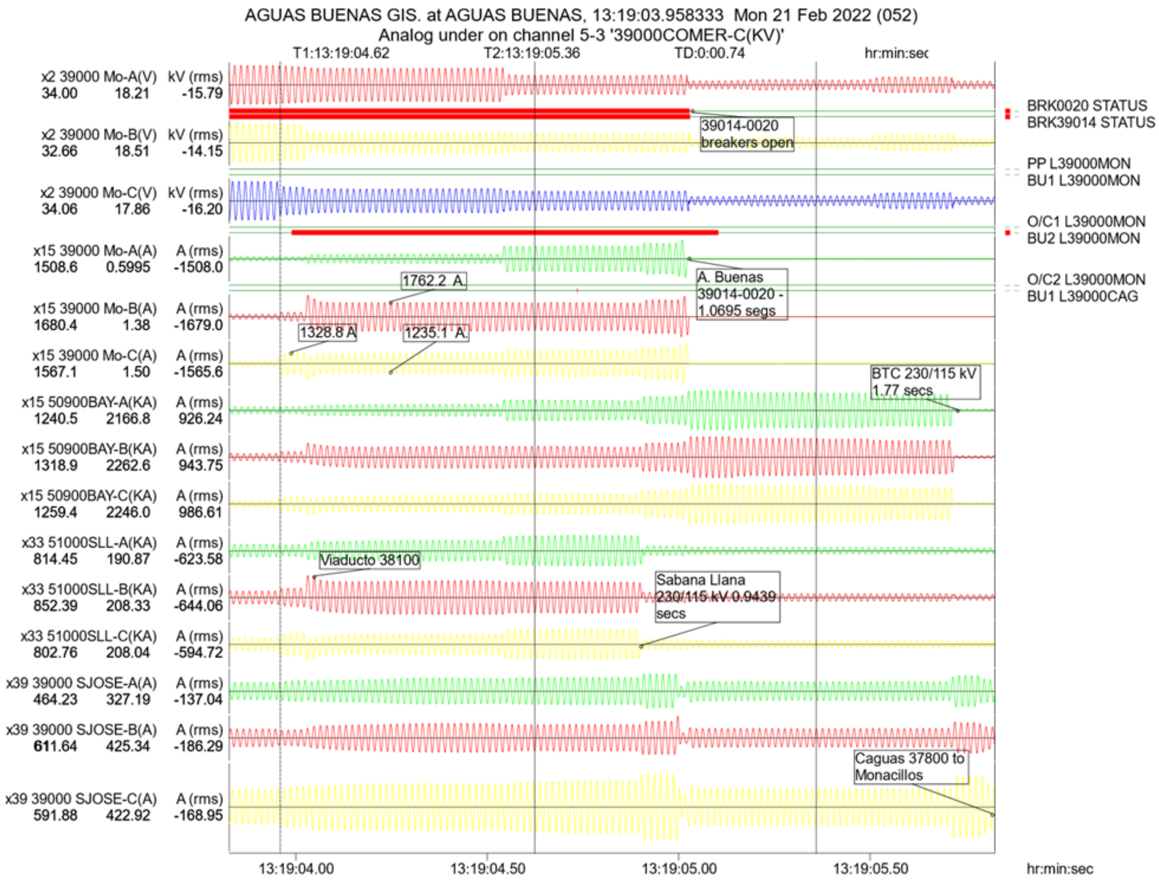


**Figure 3-24 Fault Records Data Detail**

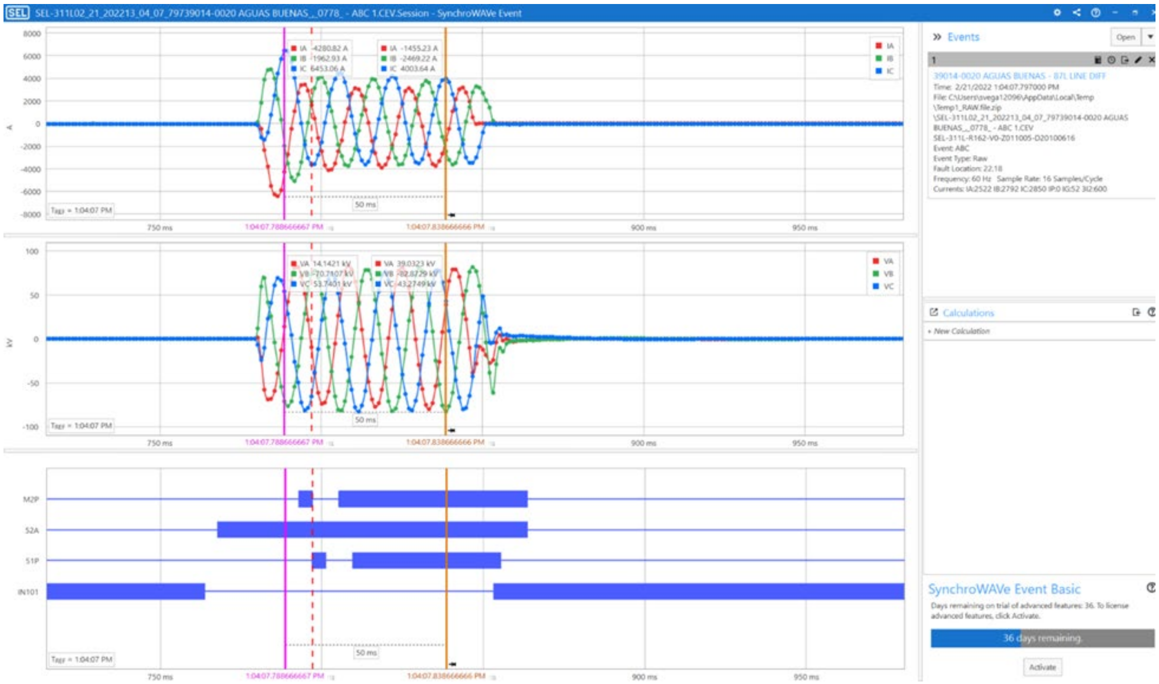


**Figure 3-25 Aguas Buenas Reclosing Event**

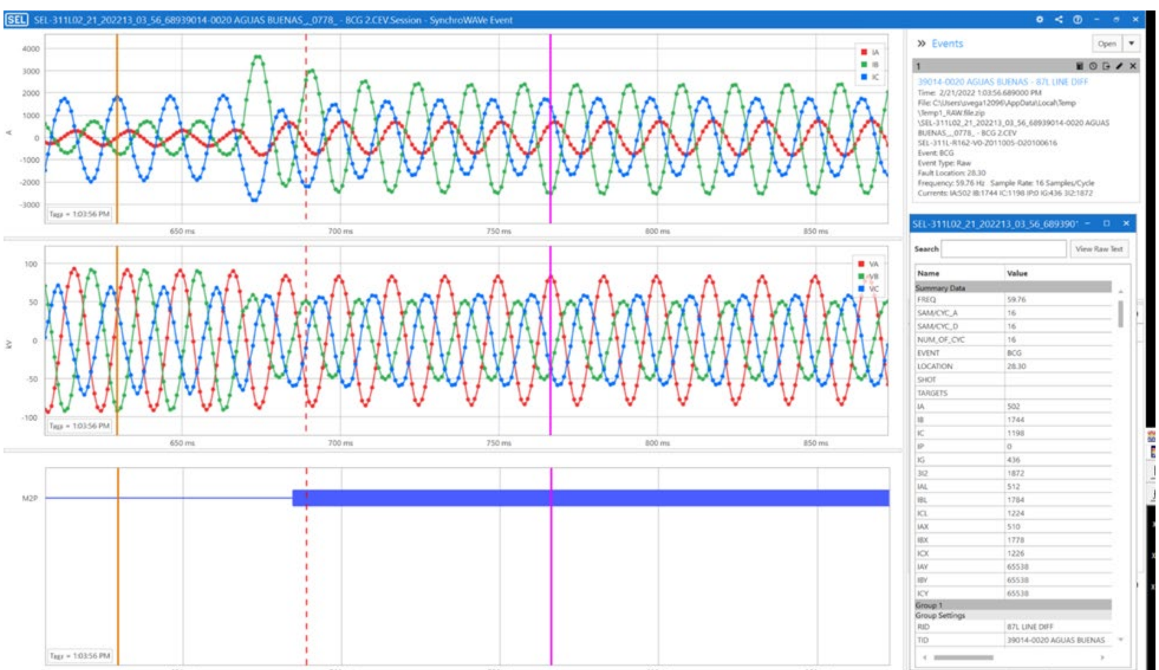


**Figure 3-26 Line 3900 Relay Fault Records Data**

### 3.5.3 Line 37800 from Caguas to Monacillos Operation

The line protection on line 37800 between Caguas and Monacillos operated 0.985 seconds after the start of the fault on line 38100. This is documented by the SEL-311L relay at the Caguas terminal on circuit breaker 20. The relay recoded the start of the fault (see Figure 3-27) as well as the moment the relay operated and interrupted the fault current (see Figure 3-28). The relay operated with a 51P element, and the relevant settings for the 51P element are shown below:

CTR = 120 51PP = 4.00 51PC = U1 51PTD = 1.47

Based on this data and a fault current of 1,060 A (prim) result with a CT ratio of 120 to a secondary fault current of 8.8 A, the anticipated tripping time is 0.995 seconds. The actual trip time of 0.985 confirms a correct relay operation.

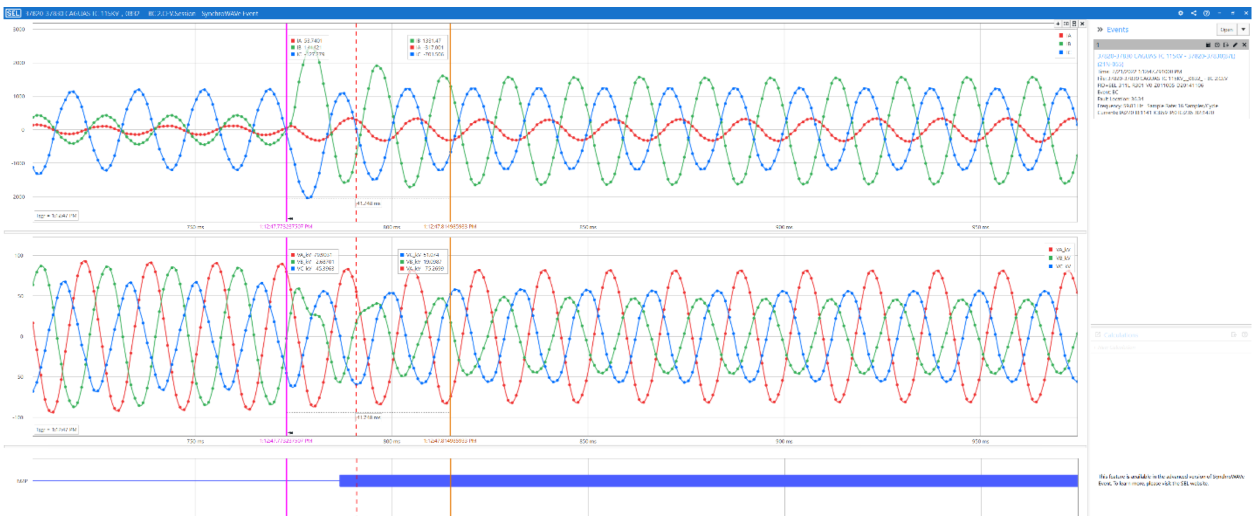

**Figure 3-27 Fault Records Data from Caguas Terminal of Line 37800 – Start of Fault**

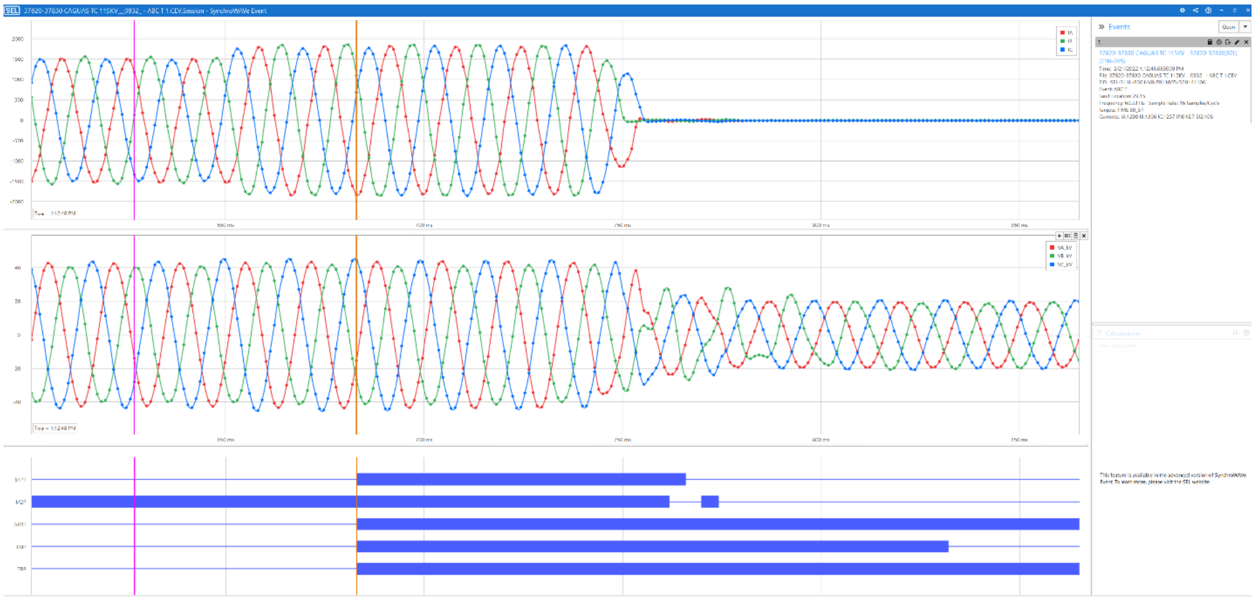

**Figure 3-28 Fault Records Data from Caguas Terminal of Line 37800 – Operation of Line**

### 3.5.4 Line 37400 from Vega Baja to Dorado Operation (37460-37440)

At 13:19:04.62, 115 kV circuit breakers 37460-37440 from Vega Baja to Dorado opened 0.72 seconds (43 cycles) after the fault at line 38100 from San Juan to Viaducto initiated. The cause of this trip is under investigation. Transient recorder at Bayamón showed that this trip caused a change in the short-circuit current feed from the south generation thru Manatí to Bayamón that affected the coordination for fault clearance at line 38100 from San Juan to Viaducto as follows:

Delayed the remote line 36800 terminal at Bayamón to San Juan's overcurrent trip. The 115 kV current present at line 36800 from Bayamón to San Juan decreased from $I_a$ = 2,597 A, $I_b$ =2,768 A, and $I_c$= 2,645 A to $I_a$=2,392 A, $I_b$=2,533 A, and $I_c$= 2,436 A.

Accelerated the 230/115 kV transformer at Bayamón's overcurrent unwanted trip. The 115 kV current present at the 230/115 kV transformer at Bayamón before line 37400's trip was $I_a$ = 3,942 A, $I_b$ =4,217 A, and $I_c$= 3,989 A. After line 37400 tripped, the current at the transformer increased to $I_a$=4,444 A, $I_b$=4,682 A, and $I_c$= 4,486 A.

[redacted]

**Figure 3-29 Diagram Shows the Bayamón TC Short-Circuit Current Feed to the 38100 Fault at San Juan SP**

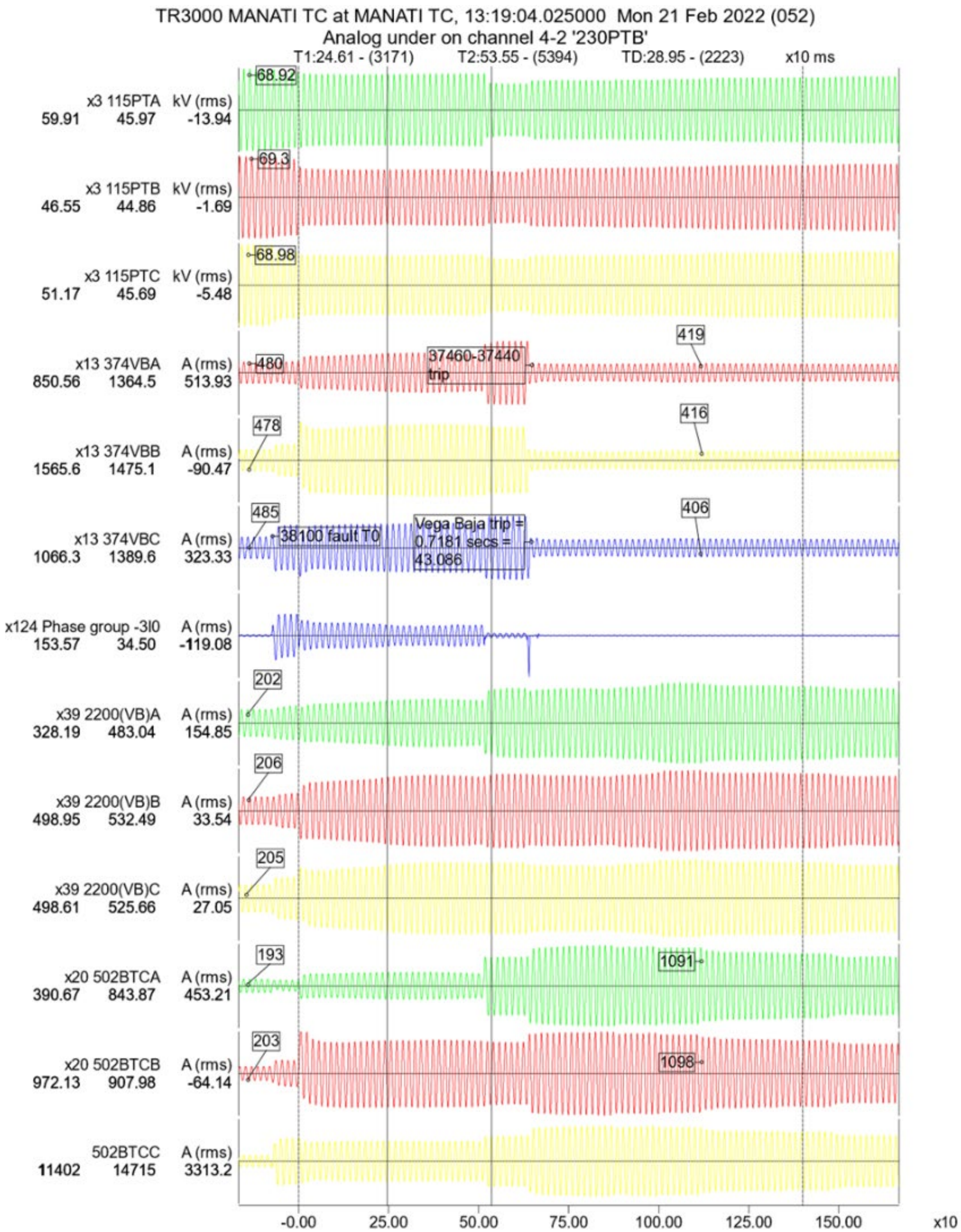


**Figure 3-30 Fault Records Data**

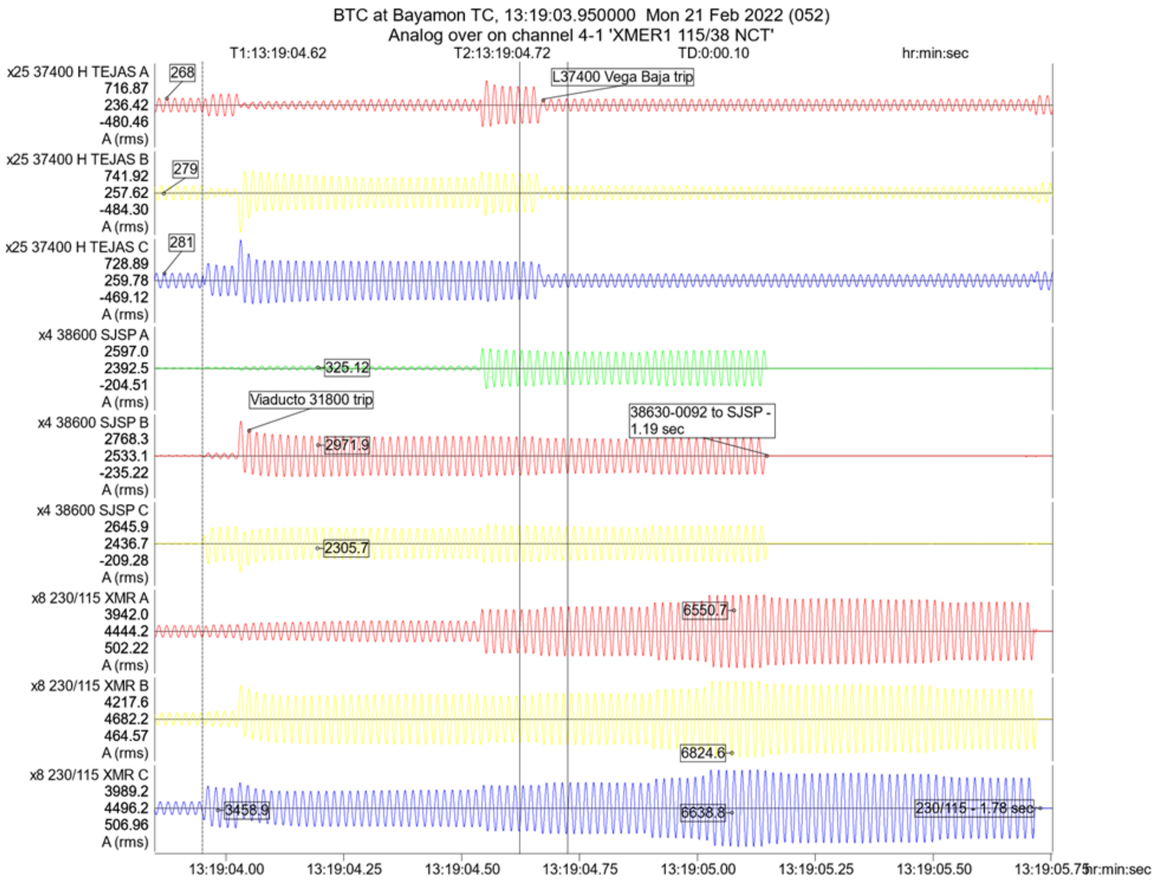


**Figure 3-31 Fault Records Data**

## 3.6 Other Events – Additional Operations Analyzed

### 3.6.1 Line 37600 from Palo Seco to Bayamón Operation (37630-0090)

The Palo Seco SP to Bayamón TC Line 37600 circuit breaker tripped in Bayamón TC.

At 13:19:06.13, the remote terminal at Bayamón to Palo Seco tripped 2.18 seconds after the fault at line 38100 from San Juan to Viaducto initiated. It was shown in the transient recorder the fault changed from C-G to C-B and finally A-B-C. Short-circuit currents observed were $I_a$= 82 A, $I_b$= 624 A, and $I_c$ = 601 A. A diminution of the short-circuit current was observed after the 230/115 kV transformer at Bayamón tripped. The 37630-0090 relay tripped with $I_a$= 317 A, $I_b$= 378 A, and $I_c$ = 307 A.

No events were received from this terminal, but accurate analysis was done using the transient recorder's analog and digital signals below.

| | | | | | |
|---|---|---|---|---|---|
| 02/21/22 1319:12 BAY TC 115 37400-5 DIFFAI SLFCHK ABNORMAL ALRM | | | transient | | Fault time |
| D 02/21/22 1319:16,233 BAY TC SOE 38600 BU PROT Status TRIP | | | time | | 13:19:03.950 |
| D 02/21/22 1319:16,294 BAY TC SOE 0092 BKR STAT Status OPEN | 16.294 | | | | |
| D 02/21/22 1319:16,317 BAY TC SOE 38630 BKR STAT Status OPEN | 16.317 | 0.023 | 13:19:05.150 | | 0:00:01.200 |
| D 02/21/22 1319:16,782 BAY TC SOE 230/115 BU Status TRIP | | | | | |
| D 02/21/22 1319:16,889 BAY TC SOE 0084 BKR STAT Status OPEN | 16.889 | 0.572 | 13:19:05.720 | 0:00:00.570 | 0:00:01.770 |
| D 02/21/22 1319:16,909 BAY TC SOE 0096 BKR STAT Status OPEN | 16.909 | 0.592 | | | |
| D 02/21/22 1319:16,917 BAY TC SOE 50230 BKR STAT Status OPEN | 16.917 | 0.6 | | | |
| D 02/21/22 1319:16,946 BAY TC SOE 230/115 BU Status NORM | | | | | |
| D 02/21/22 1319:17,232 BAY TC SOE 0020 BKR STAT Status OPEN | 17.232 | 0.915 | 13:19:06.070 | 0:00:00.920 | 0:00:02.120 |
| D 02/21/22 1319:17,236 BAY TC SOE 4340 BKR STAT Status OPEN | 17.236 | 0.919 | | | |
| D 02/21/22 1319:17,275 BAY TC SOE 37600 LDIFTRP Status TRIP | | | | | |
| D 02/21/22 1319:17,276 BAY TC SOE 37600 BU PROT Status TRIP | | | | | |
| D 02/21/22 1319:17,276 BAY TC SOE 37600 CAR P10 Status TRIP | | | | | |
| D 02/21/22 1319:17,301 BAY TC SOE 37630 BKR STAT Status OPEN | 17.301 | 0.984 | 13:19:06.130 | 0:00:00.980 | 0:00:02.180 |

**Figure 3-32 SOE Records Data**

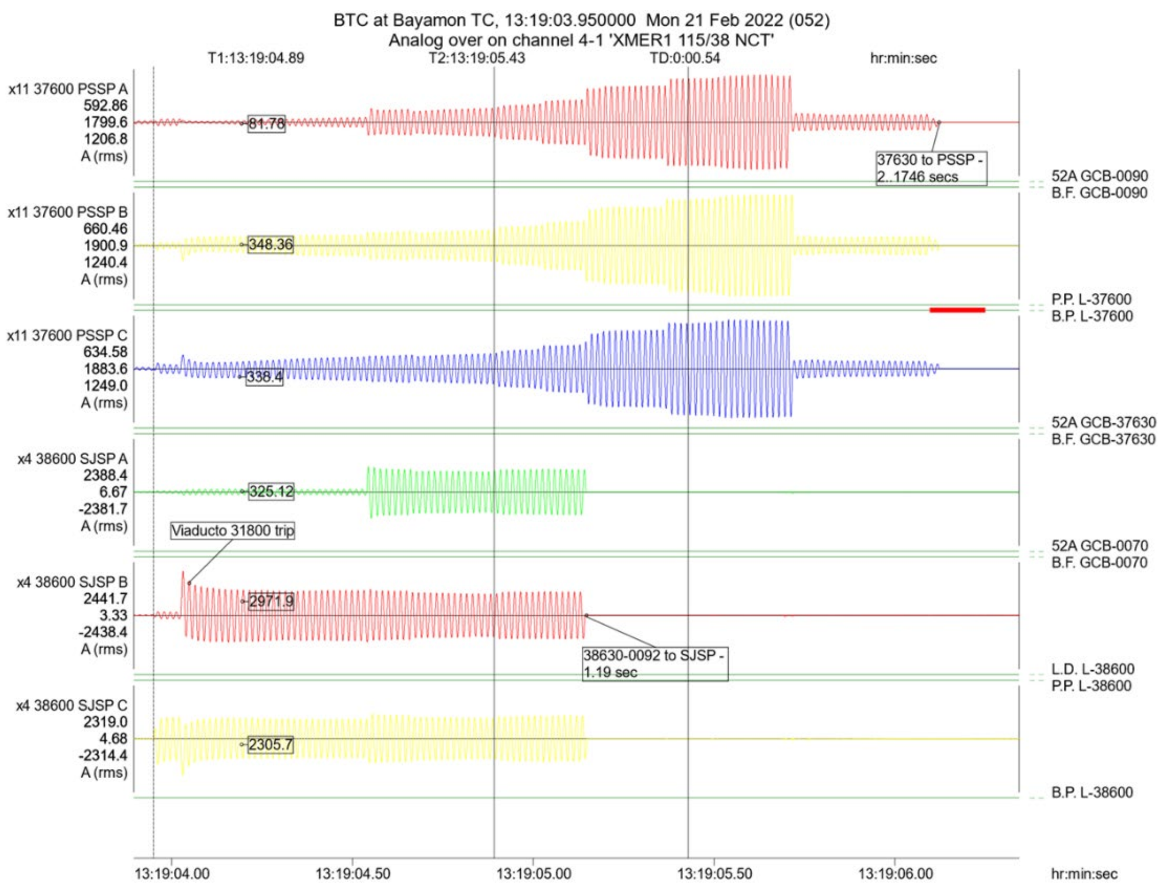


**Figure 3-33 Line 37600 Remote Back-up Operation**

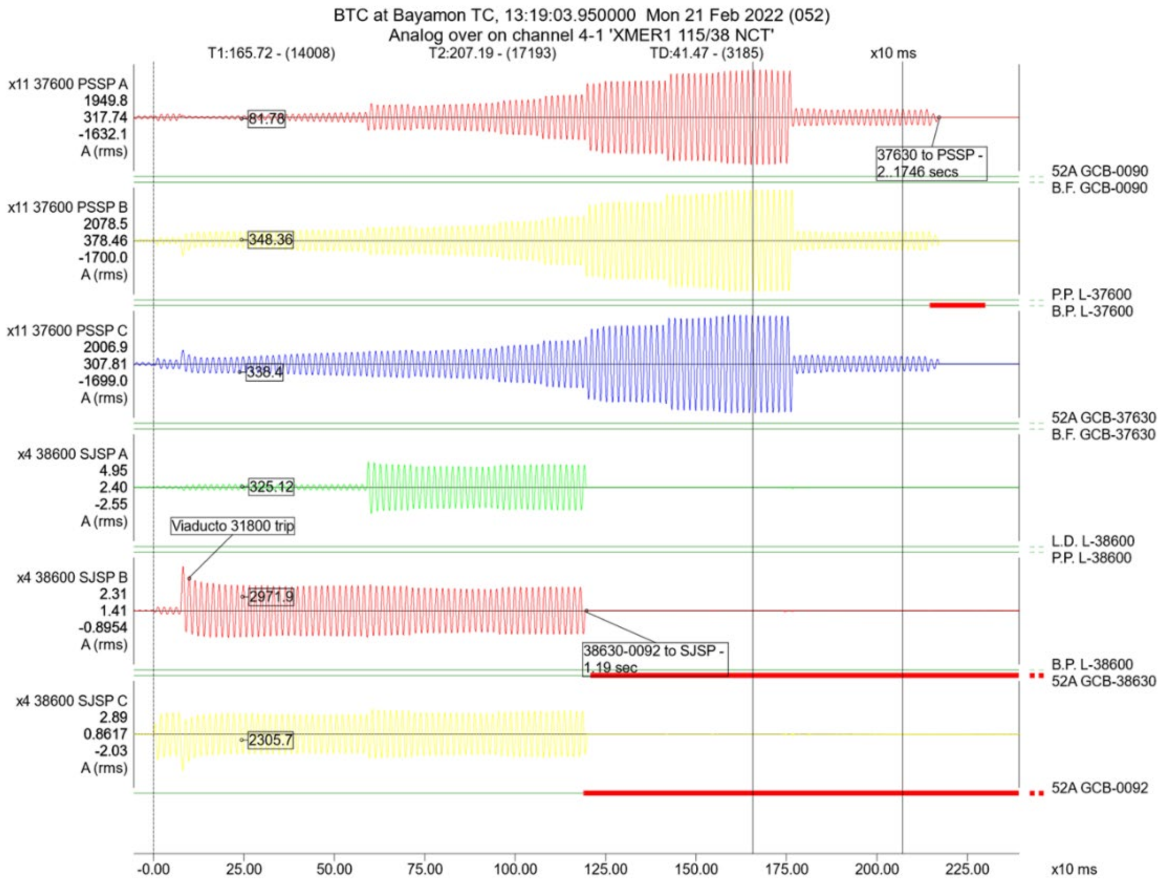


**Figure 3-34 Fault Records Data**

### 3.6.2 Line 37700 from Palo Seco to Bayamón Operation (37730-0086)

The Palo Seco SP to Bayamón TC Line 37700 circuit breaker in Palo Seco did not trip. Root cause was that the backup unit elements reset, or the current magnitude fell below pickup values.

Zone 3 impedance element with 120 cycles as trip time asserted and deactivated during the fault. See figure below. Zone 2 element deactivated, and the 51P element current value went below the pickup. event.

From the relay record, maximum short-circuit currents before the transformer tripped observed in this line were at $I_a$=1,725 A, $I_b$= 2,000 A, and $I_c$ =2,022 A. Decrease of the short-circuit current was observed after the 230/115 kV transformer at Bayamón tripped: $I_a$=316 A, $I_b$=348 A, and $I_c$ =332 A. Refer to protection event and settings below.

Neither the protection nor SCADA show line 37700 from Bayamón to Palo Seco tripped.

| | | | | | |
|---|---|---|---|---|---|
| 02/21/22 1319:12 BAY TC 115 37400-5 DIFFAI SLFCHK ABNORMAL ALRM | | | transient | | Fault time |
| D 02/21/22 1319:16,233 BAY TC SOE 38600 BU PROT Status TRIP | | | time | | 13:19:03.950 |
| D 02/21/22 1319:16,294 BAY TC SOE 0092 BKR STAT Status OPEN | 16.294 | | | | |
| D 02/21/22 1319:16,317 BAY TC SOE 38630 BKR STAT Status OPEN | 16.317 | 0.023 | 13:19:05.150 | | 0:00:01.200 |
| D 02/21/22 1319:16,782 BAY TC SOE 230/115 BU Status TRIP | | | | | |
| D 02/21/22 1319:16,889 BAY TC SOE 0084 BKR STAT Status OPEN | 16.889 | 0.572 | 13:19:05.720 | 0:00:00.570 | 0:00:01.770 |
| D 02/21/22 1319:16,909 BAY TC SOE 0096 BKR STAT Status OPEN | 16.909 | 0.592 | | | |
| D 02/21/22 1319:16,917 BAY TC SOE 50230 BKR STAT Status OPEN | 16.917 | 0.6 | | | |
| D 02/21/22 1319:16,946 BAY TC SOE 230/115 BU Status NORM | | | | | |
| D 02/21/22 1319:17,232 BAY TC SOE 0020 BKR STAT Status OPEN | 17.232 | 0.915 | 13:19:06.070 | 0:00:00.920 | 0:00:02.120 |
| D 02/21/22 1319:17,236 BAY TC SOE 4340 BKR STAT Status OPEN | 17.236 | 0.919 | | | |
| D 02/21/22 1319:17,275 BAY TC SOE 37600 LDIFTRP Status TRIP | | | | | |
| D 02/21/22 1319:17,276 BAY TC SOE 37600 BU PROT Status TRIP | | | | | |
| D 02/21/22 1319:17,276 BAY TC SOE 37600 CAR P10 Status TRIP | | | | | |
| D 02/21/22 1319:17,301 BAY TC SOE 37630 BKR STAT Status OPEN | 17.301 | 0.984 | 13:19:06.130 | 0:00:00.980 | 0:00:02.180 |

**Figure 3-35 SOE Records Data**


**Figure 3-36 Zone 2 and Zone 3 Elements Incorrectly Deactivated and 51P Element Deactivated**

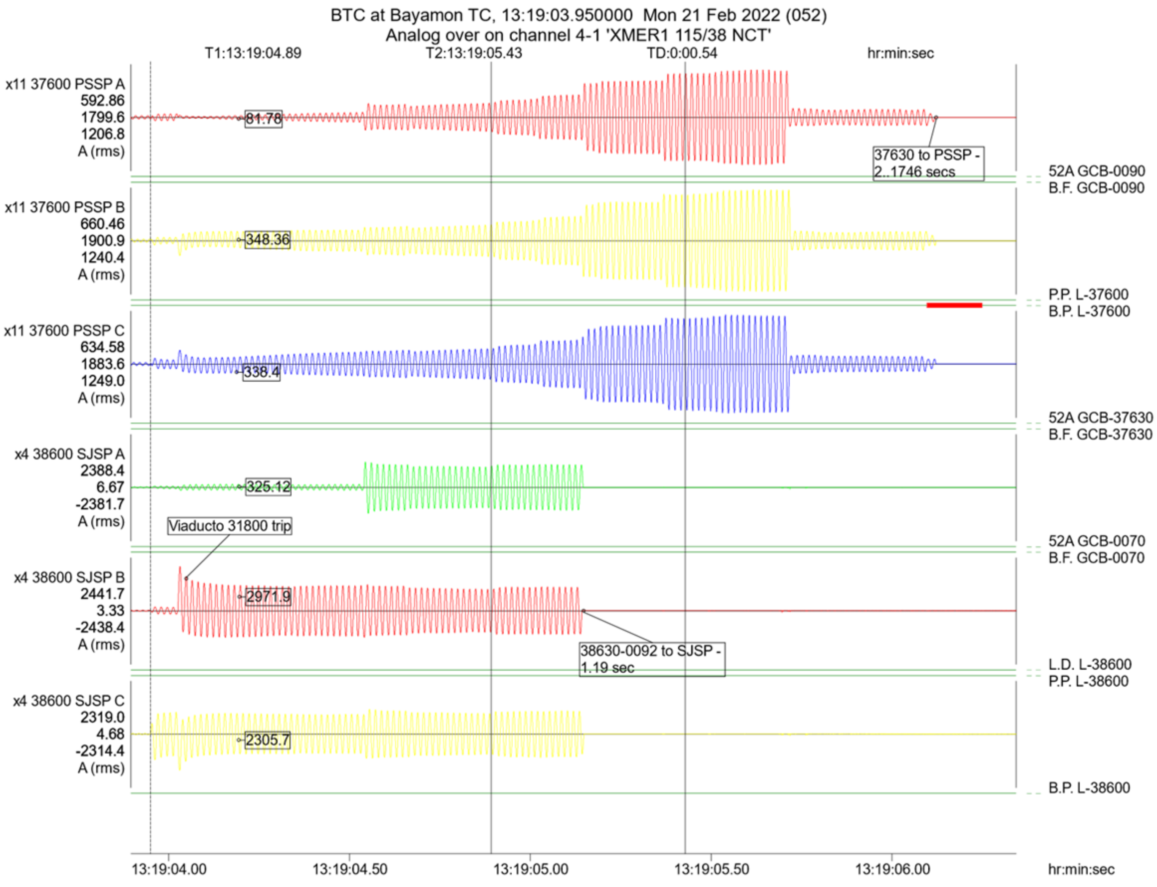


**Figure 3-37 Fault Records Data**

### 3.6.3 Palo Seco Generation Unit #3 Operation

As per the report received from PREPA, Palo Seco Generation Unit #3 was generating 110 MW prior to the event.

During the disturbance, the turbine revolutions reached 3750 r/min. The generation unit had a sudden load loss and tripped.

The generator trip was caused by loss of electric power to the forced draft fans and to the induced draft fans of the boiler (first out, loss of FDFs, and IDFs).

Note that the times reported are different than the times recorded in LUMA's SCADA due to different time sources.

Palo Seco Unit #3 issued a sequential trip 1.823 seconds after the fault at line 38100 began. Circuit breakers 0030-0032 opened 3.889 seconds after the fault initiated.

The transient-recorder frequency is in accordance with the 3750 r/min = 62.5 Hz reported at Palo Seco.

| |
|---|
| D 02/21/22 1319:05,726 PALOSECO SOE GEN3 SEQU TRP Status TRIP |
| D 02/21/22 1319:06,076 PALOSECO SOE 38700 CAR Status TRIP |
| D 02/21/22 1319:07,779 PALOSECO SOE GEN3 LO Status TRIP |
| D 02/21/22 1319:07,779 PALOSECO SOE UNIT3 LO Status TRIP |
| D 02/21/22 1319:07,792 PALOSECO SOE 0032 BKR STAT Status OPEN |
| D 02/21/22 1319:07,792 PALOSECO SOE 0030 BKR STAT Status OPEN |
| D 02/21/22 1319:07,844 PALOSECO SOE GEN3 SEQU TRP Status NORM |
| 02/21/22 1319:09 PALOSECO 115 0032 BKR STATUS OPEN |
| 02/21/22 1319:09 PALOSECO 115 0032 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:09 PALOSECO 115 0030 BKR STATUS OPEN |
| 02/21/22 1319:09 PALOSECO 115 0030 BKR BKR ABNORMAL OPEN |

**Figure 3-38 SOE Records Data**

### 3.6.4 Line 38900 from Hato Rey to Martín Peña Operation

The protection relay on line 38900 at the Martín Peña terminal tripped the line correctly with a Zone 2 and Zone 4 operation, 1.5 seconds after the BC-ground fault started. The relay's time is not synchronized to a common time base. The time relation to a GPS clock was performed by manually synchronizing the voltage profile recorded in the relay record with the voltage profile recorded by the fault recorder in the Hato Rey substation. The fault-recorder time is synchronized with a GPS clock. The change from symmetrical three-phase depressed voltages to an even more decline voltage in A-phase was used to synchronize the two records.

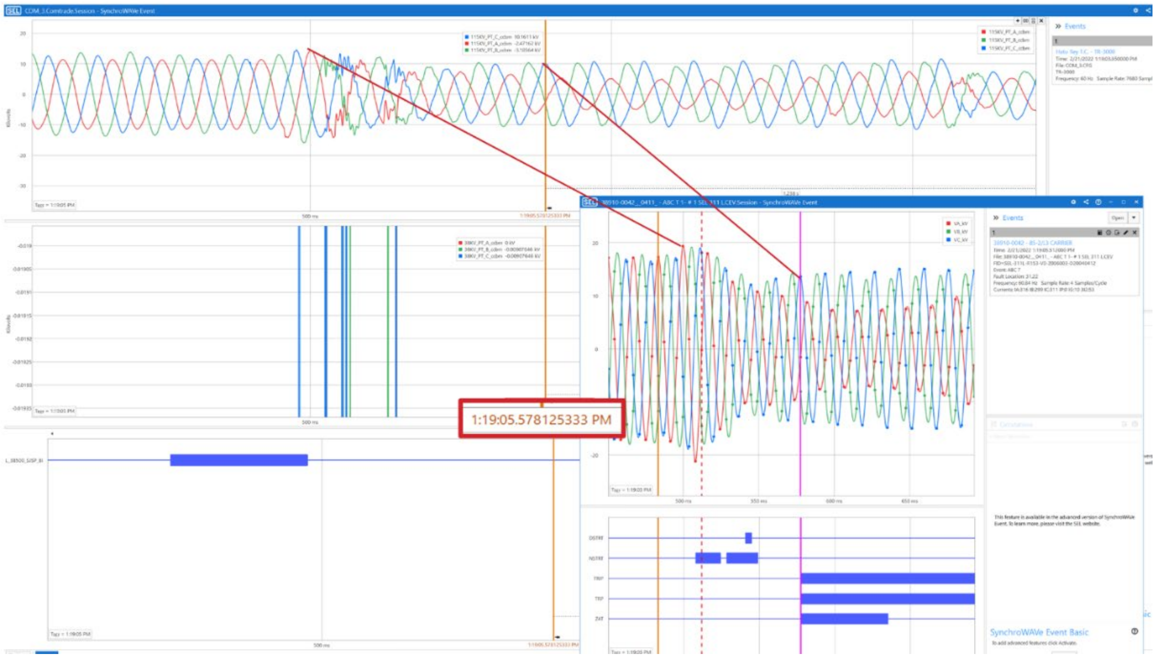


**Figure 3-39 Fault Records Data from Martin Peña Terminal of Line 38900 – Trip Command**

### 3.6.5 Line 40500 from Monacillos to Hato Rey Operation

The protection relays located on the Monacillos terminal of line 40500 operated with a Zone 3 distance element after 1.5 seconds. Both relays, the SEL-311L, and the SEL-311C, have the same backup protection settings and issued a trip command at the same time. The tripping time was synchronized with the global time based on voltage comparison of the voltage in the relay record and the voltage recorded by a fault recorder in the Monacillos substation. The increase of symmetrical voltages from 16.6 kV to 27 kV after the line tripping was used to synchronize the timing. The result was that it could be confirmed that the relays indeed tripped 1.5 seconds after the fault on line 38100 started.

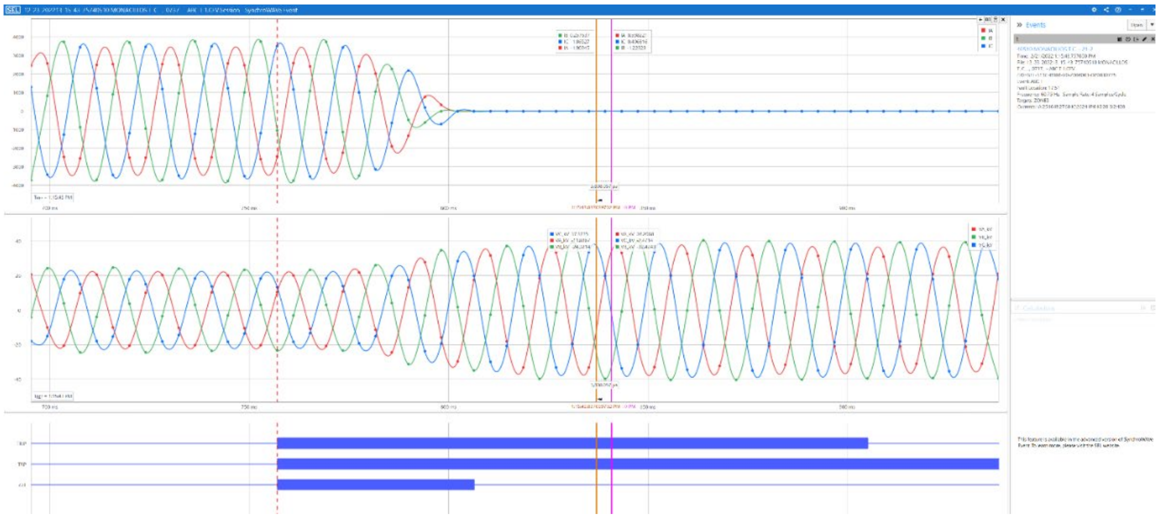

**Figure 3-40 Fault Records Data from Monacillos Terminal of Line 40500 – Operation of Line**

### 3.6.6 Line 37500 from Rio Bayamón to Monacillos Operation

The line protection on line 37500 between Rio Bayamón and Monacillos operated 1.363 seconds after the start of the fault on line 38100. This is documented by the SEL-311L relay at the Rio Bayamón terminal on circuit breaker 20. The relay recoded the start of the fault (see figure 3-41) as well as the moment, the relay operated and interrupted the fault current (see figure 3-42). The relay operated with a 51P element, and the relevant settings for the 51P element are shown below:

CTR = 400 51PP = 0.50 51PC = C1 51PTD = 0.26

Based on this data and a fault current of 1,420 A (prim), which results in a CT ratio of 400 to a secondary fault current of 3.55 A, the anticipated tripping time is 0.91 seconds. The actual trip time of 1.363 can be explained by the fact that the fault current varied during the fault, as visible in the two records. At the beginning of the fault, the fault current was 780 A (prim) or 1.95 A (sec), which would have resulted in a tripping time of 1.32 seconds.

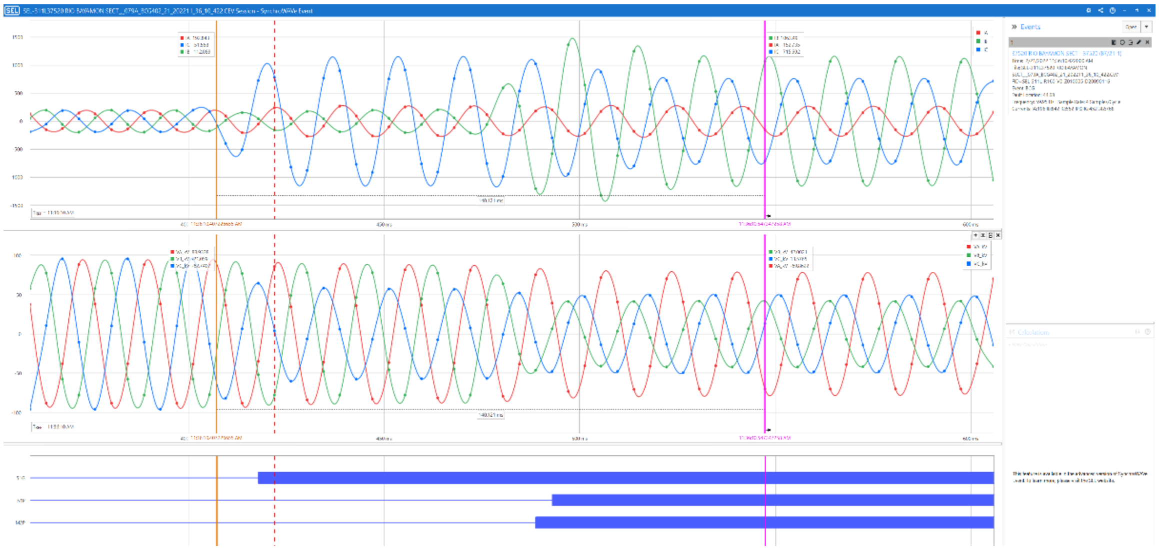

**Figure 3-41 Fault Records Data from Monacillos Terminal of Line 37500 – Start of Fault**

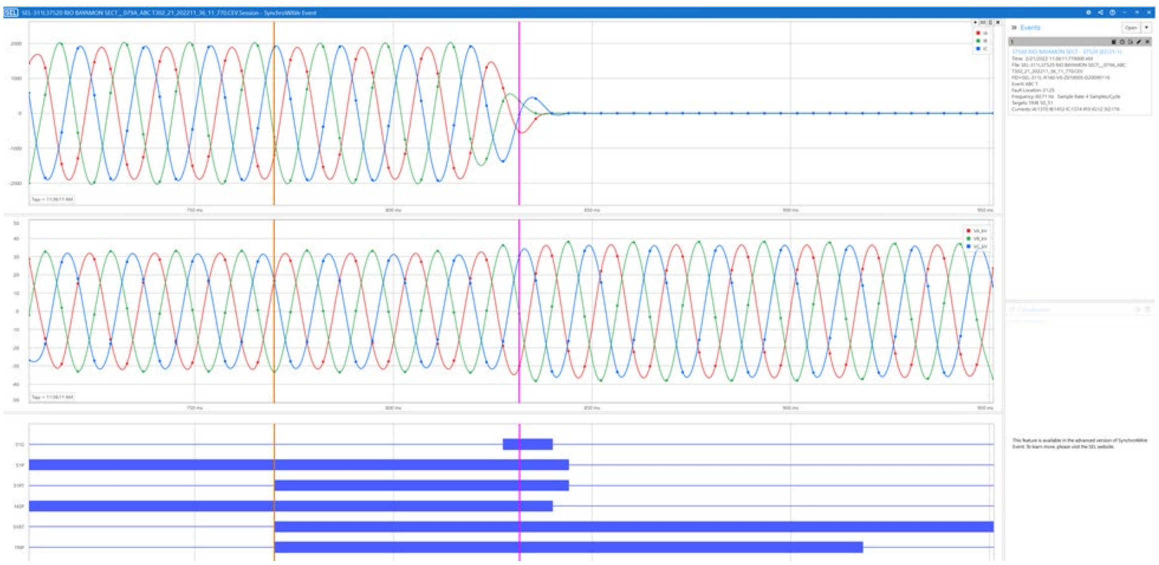

**Figure 3-42 Fault Records Data from Monacillos Terminal of Line 37500 – Operation of Line**

### 3.6.7 Line 38900 from Berwind to Martin Peña Operation

The line protection on line 38900 between Berwind to Martin Peña operated 1.5 seconds after the start of the fault on line 38100. This is documented by the SEL-311L relay at the Berwind terminal on circuit breaker 30. The relay recoded the start of the fault (see Figure 3-43) as well as the moment the relay operated and interrupted the fault current (see Figure 3-44). The relay operated correctly with a Z4 distance element that is set with a 1.5 second delay and a zone reach of 16.41 ohms.

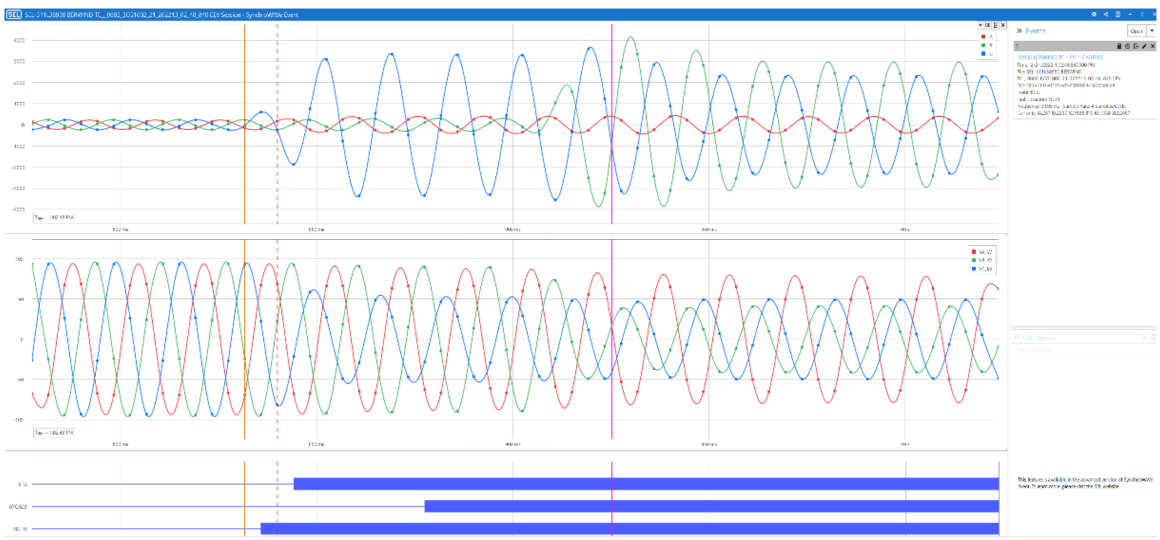

**Figure 3-43 Fault Records Data from Berwind Terminal of Line 38900 – Fault Start**

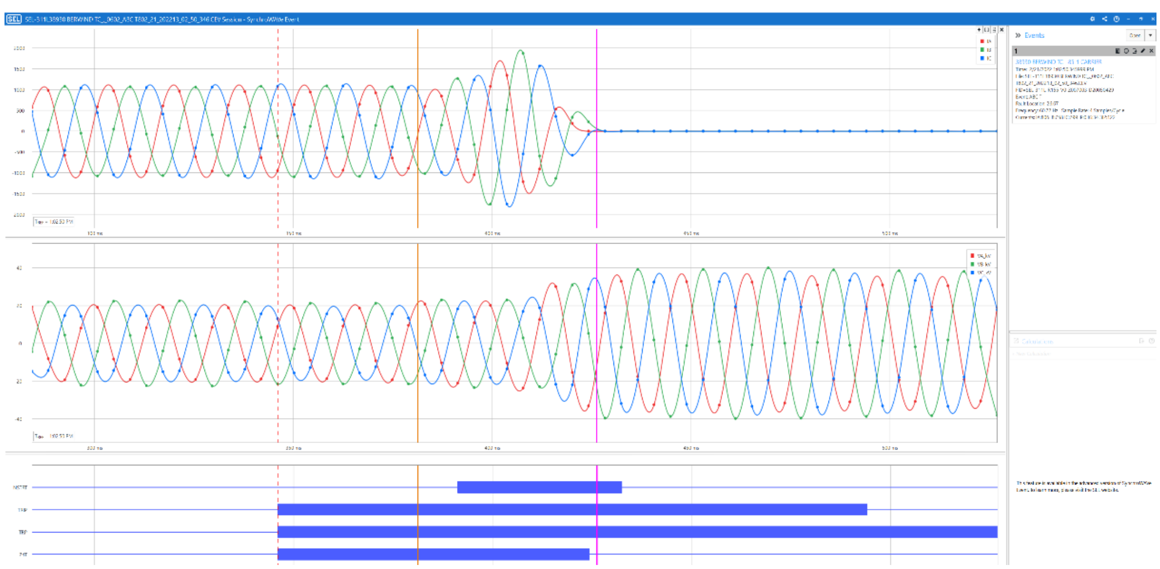

**Figure 3-44 Fault Records Data from Berwind Terminal of Line 38900 – Operation of Line**

### 3.6.8 Bayamón 230/115 kV Transformer Operation (50230-0096/0084-0092)

LUMA's Substations Maintenance team informed IGCV-51 phase B tripped.


**Figure 3-45 IGCV-51 Phase B with Flag of Time-Delay Operation**

At 13:19:06.077, the 230/115 kV transformer at Bayamón Transmission Center and circuit breakers 50230-0096/0084-0092 tripped. Targets found were 230 kV phase backup (51P) from the IGCV-51 relay. From the transient recorder, the transformer tripped 1.777 seconds after the fault at line 38100 from San Juan to Viaducto initiated.

The fault at line 38100 began as a C-G fault for four cycles. The fault evolved to B-C and currents at the transformer were $I_a$ = 1,915 A, $I_b$= 4,527 A, and $I_c$= 3,141 A. The fault evolved to a three-phase fault after 0.59 seconds. After 1.12 seconds into the fault, before line 38600 from Bayamón to San Juan tripped, the currents were $I_a$=6,551 A, $I_b$ = 6,825 A, and $I_c$ = 6,639 A. When line 38600 tripped, the current at the transformer was sustained at $I_a$ = 5,756, $I_b$= 6,080 A, and $I_c$ 5,982 A.

The main cause for this unwanted trip was the loss of coordination of the overcurrent element due to increase in short-circuit current at the transformer when key elements trip unexpectedly as follows:

1. Line 37400 to Vega Baja incorrect trip 0.72 seconds after the fault at line 38100 initiated. Before line 37400 tripped, the 115 kV current present at the 230/115 kV at Bayamón was $I_a$ = 3,942 A, $I_b$ = 4,217 A, $I_c$= 3,989 A. After line 37400 trips, the current at the transformer increased to $I_a$= 4,444 A, $I_b$= 4,682 A, and $I_c$= 4,486 A.
2. 230/115 kV at Sabana Llana incorrectly trips. Before 230/115 kV at Sabana Llana tripped, the 115 kV current present at the 230/115 kV at Bayamón was $I_a$ = 4,444 A, $I_b$= 4,682 A, and $I_c$= 4,486 A. After the transformer tripped, the current at the transformer increased to $I_a$= 5,214 A, $I_b$ = 5,447 A, and $I_c$= 5,181 A.
3. 115 kV line 39100 at Aguas Buenas to Monacillos trips one second after the fault at line 38100 is initiated. Before line 39100 tripped, the 115 kV current present at the 230/115 kV at Bayamón was $I_a$= 5,214 A, $I_b$= 5,447 A, and $I_c$= 5,181 A. After line 39100 trips, the current at the transformer increased to $I_a$ = 6,551 A, $I_b$ = 6,824 A, and $I_c$ = 6,638 A.

It is recommended that the coordination of this 230/115 kV transformer be reviewed with priority.

These elements are the ones that feed the North side 115 kV's with the South's generation. As the San Juan and Palo Seco plants reflect most of the generation out of service, this is an issue in the North area's coordination.

| |
|---|
| 02/21/22 1319:06 BAY TC 115 38630 BKR STATUS OPEN |
| 02/21/22 1319:06 BAY TC 115 38630 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:06 BAY TC 115 0092 BKR STATUS OPEN |
| 02/21/22 1319:06 BAY TC 115 0092 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:06 BAY TC 115 0084 BKR STATUS OPEN |
| 02/21/22 1319:06 BAY TC 115 0084 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:06 BAY TC 230 50230 BKR STATUS OPEN |
| 02/21/22 1319:06 BAY TC 230 50230 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:06 BAY TC 230 0096 BKR STATUS OPEN |
| 02/21/22 1319:06 BAY TC 230 0096 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:08 BAY TC 38 4340 BKR STATUS OPEN |
| 02/21/22 1319:08 BAY TC 38 4340 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:08 BAY TC 38 0020 BKR STATUS OPEN |
| 02/21/22 1319:08 BAY TC 38 0020 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:08 BAY TC 115 37630 BKR STATUS OPEN |
| 02/21/22 1319:08 BAY TC 115 37630 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:08 BAY TC 115 0090 BKR STATUS OPEN |
| 02/21/22 1319:08 BAY TC 115 0090 BKR BKR ABNORMAL OPEN |
| 02/21/22 1319:12 BAY TC 38 9800-2 DIFFAIL STATUS ALRM |
| 02/21/22 1319:12 BAY TC 38 9800-2 DIFFAIL SLFCHK ABNORMAL ALRM |
| 02/21/22 1319:12 BAY TC 115 37500-1 DIF1FA STATUS ALRM |
| 02/21/22 1319:12 BAY TC 115 37500-1 DIF1FA SLFCHK ABNORMAL ALRM |
| 02/21/22 1319:12 BAY TC 115 37500-1 DIF2FA STATUS ALRM |
| 02/21/22 1319:12 BAY TC 115 37500-1 DIF2FA SELFCHK2 ABNORM ALRM |
| 02/21/22 1319:12 BAY TC 115 37400-5 DIFFAI STATUS ALRM |
| 02/21/22 1319:12 BAY TC 115 37400-5 DIFFAI SLFCHK ABNORMAL ALRM |
| D 02/21/22 1319:16,233 BAY TC SOE 38600 BU PROT Status TRIP |
| D 02/21/22 1319:16,294 BAY TC SOE 0092 BKR STAT Status OPEN |
| D 02/21/22 1319:16,317 BAY TC SOE 38630 BKR STAT Status OPEN |
| D 02/21/22 1319:16,782 BAY TC SOE 230/115 BU Status TRIP |
| D 02/21/22 1319:16,889 BAY TC SOE 0084 BKR STAT Status OPEN |
| D 02/21/22 1319:16,909 BAY TC SOE 0096 BKR STAT Status OPEN |
| D 02/21/22 1319:16,917 BAY TC SOE 50230 BKR STAT Status OPEN |
| D 02/21/22 1319:16,946 BAY TC SOE 230/115 BU Status NORM |
| D 02/21/22 1319:17,232 BAY TC SOE 0020 BKR STAT Status OPEN |
| D 02/21/22 1319:17,236 BAY TC SOE 4340 BKR STAT Status OPEN |
| D 02/21/22 1319:17,275 BAY TC SOE 37600 LDIFTRP Status TRIP |
| D 02/21/22 1319:17,276 BAY TC SOE 37600 BU PROT Status TRIP |
| D 02/21/22 1319:17,276 BAY TC SOE 37600 CAR P10 Status TRIP |
| D 02/21/22 1319:17,301 BAY TC SOE 37630 BKR STAT Status OPEN |

**Figure 3-46 SOE Records Data**

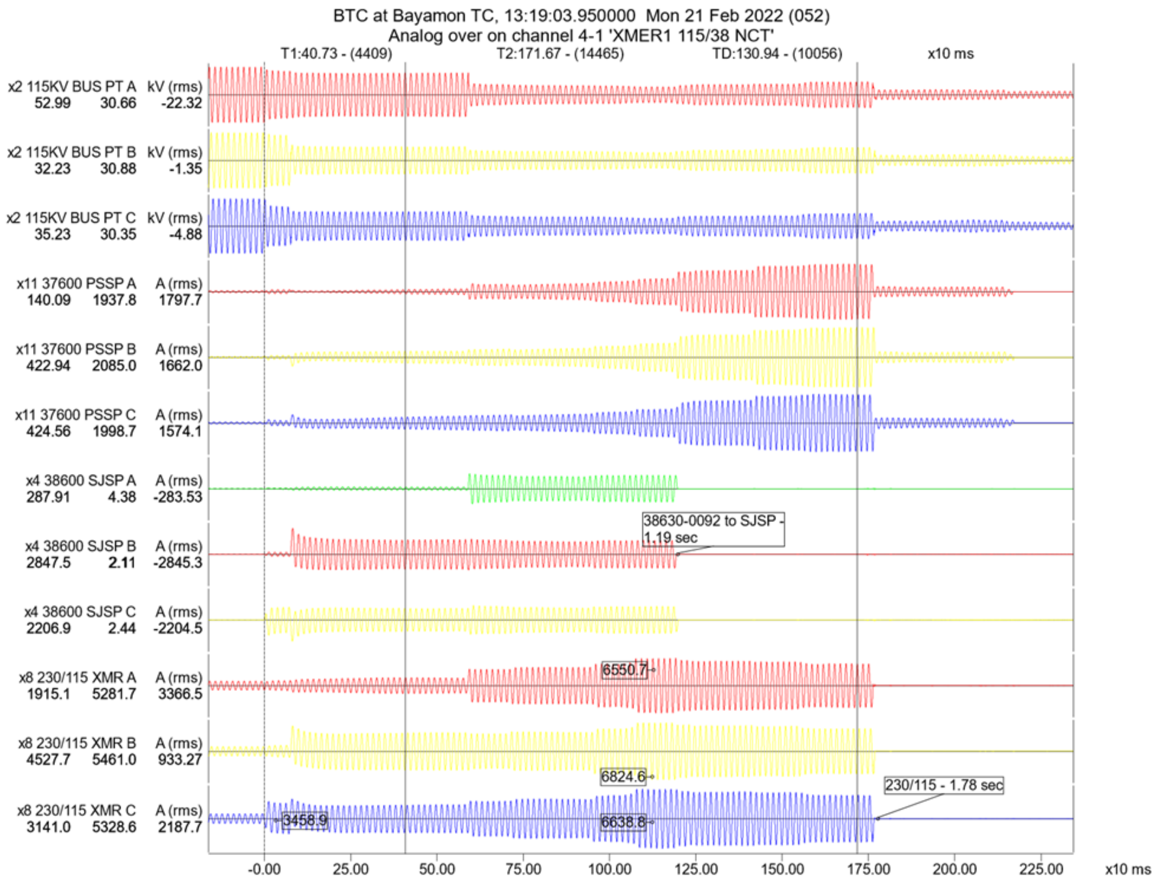


**Figure 3-47 Fault Records Data**

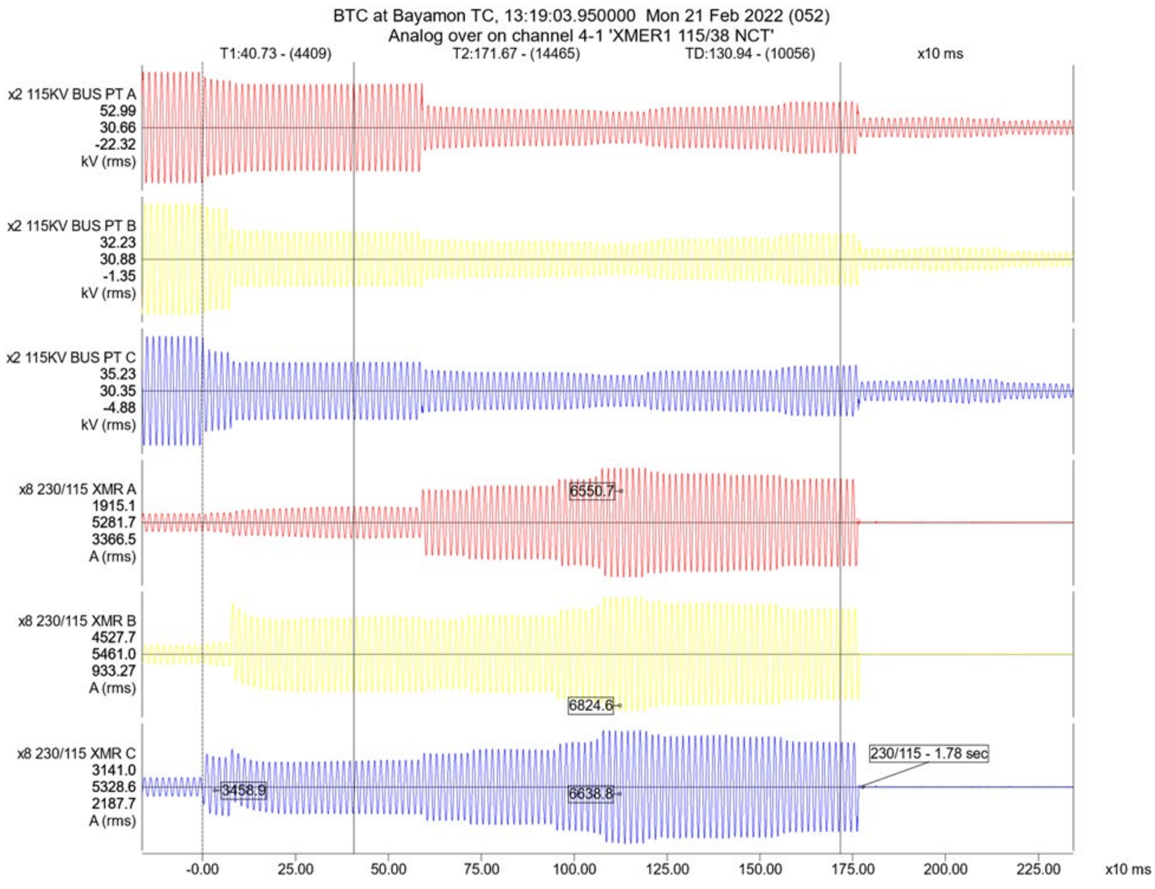


**Figure 3-48 Fault Records Data**

## 3.7 Other Events – Operations Not Analyzed

Additional operations have been identified at the later stage of the outage due to the cascading effect of the disturbance. These operations are not considered of major concern but are listed below to be included in the studies of the protection-scheme revisions recommended in Section 3.4:

- Line 36800 Fajardo - Palmer
- Line 36200 Rio Blanco – Juncos – Monacillos.

# 4. Summary and Conclusion

During the immediate response to this event, LUMA focused on safety, restoration of service to customers, restoring the system's stability, and assuring continuation of service within operating parameters.

Despite the aging of the infrastructure and the large-scale outages that occurred, power was restored to almost all customers within three hours.

The following is the list of the major findings from the investigation:

**Table 4 Major Findings**

| Issue | Finding |
|---|---|
| Fault in line 38100. | Vegetation flashover. |
| Circuit breaker fails to operate in San Juan. | Lack of dc. Short circuit due to degraded insulation by aging. |
| Fault in line 38400. | Flashover from initial fault. Lines sharing right of way. Fault cleared properly. |
| Breaker failure in SJSP relay fails to operate. | Damaged wiring from the current transformers due to aging. |
| 115 kV remote ends of San Juan trip. | Protection backup systems operate to clear the fault in line 38100. Loss of San Juan Generation Units. |
| Cascading outage. | Trips in 230 kV transformers in Bayamón TC and Sabana Llana. Loss of Palo Seco Generation Unit #3. Additional remote trips. |

In conclusion, a routine power-line fault followed by the lack of dc power to the associated circuit breakers coupled with the inaction of the backup protective scheme resulted in the fault evolving beyond the zone of protection that ultimately resulted in the large-scale interruption of service.

LUMA is presently working on addressing all the key action points included in the section below and continues to use the lessons learned to improve the plan to rebuild the grid's resiliency in Puerto Rico and prevent similar incidents in the future.

# 5. Next Steps

While addressing the scope of these legacy infrastructure challenges will take time, LUMA is determined to continue improving immediate reliability issues by making the necessary short-term repairs, as well as transforming the resilience of the grid over the long-term by advancing FEMA projects.

## 5.1 Short-Term Actions

The short-term actions identified to help improve the grid's resiliency and scheduled to be completed by LUMA before the end of July 2022 are presented below.

### 5.1.1 DC Monitoring in San Juan SP

LUMA's Substations Maintenance team is developing a plan to include dc circuit monitoring for circuit breakers. Final plan and schedule will be completed the week of 3/21.

Scheduling for San Juan SP and confirming proper wiring are expected to take two to three weeks to ensure no accidental trips/outages occur. These improvements will be coordinated with the control center.

### 5.1.2 DC Monitoring in Additional Substations

LUMA's Substations Maintenance team is developing a schedule by the week of 3/14 to implement dc circuit monitoring for circuit breakers in Viaducto TC, Monacillos TC, Bayamón TC, Costa Sur, and Sabana Llana TC. These substations were chosen based on weighing parameters, such as: station loading, asset health, age, and single point of failure.

These substations will be scheduled and planned to coordinate with other substation work.

### 5.1.3 Assessment of Existing Renovation Project

As the first two contingencies were due to failing aging equipment, the energization of the San Juan SP protection and control system upgrade and 38 kV gas-insulated switchgear project will be scheduled for assessment. These systems have been constructed more than a decade ago and never placed into service. A draft assessment plan was completed.

The San Juan 115 kV and 38 kV switchyards renovation project was part of the Units #5 and #6 repowering projects that PREPA initiated in 1997.

The protection and control panels have been installed for more than 10 years and some of the electronic devices may be obsolete.

The scope of the project consisted of several stages:

**38 kV:**

- 100% replacement of the 38 kV switchyard by GIS (Siemens).
- New protection systems for all lines and transformers (ESST 5-6, ESST 7-8, ESST 9-10, 115/30 kV T1, 115/38 kV T2) connected to the 38 kV switchyard.
- The configuration of the 38 kV GIS is comprised of two normal busbars and one auxiliary busbar.
- Replacement of the primary protection in the remote substations of all the 38 kV lines.

**115 kV:**

- Extension of the existing switchyard with a GIS of nine circuit breakers in a breaker and a half configuration (AREVA).
- Replacement of all line protection and transformers connected to the 115 kV switchyard.
- Replacement of all Generator 7, 8, 9, and 10 protections.

Installation of two transient recorders (115 kV and 38 kV), new RTU, and DCS

In total, over 350 protection relays in 35+ protection panels have been installed.

Additional recommendations include:

- Evaluate the condition of Transformer #2 115/38 kV.
- Revise existing cutover plan to transfer of the 38 kV circuits to the new GIS.
- Determine the scope of work of the 115 kV GIS project, in coordination with the G&T demarcation and underground loop repair project.

### 5.1.4 Functional Circuit Breaker Testing

Continue with functional relay to circuit breaker testing systematically.

### 5.1.5 Specific Corrective Actions Identified During the Event

1. Revision of the protection schemes of 230/115 kV transformers at Bayamón TC and Sabana Llana TC.
2. Revision of protection schemes for lines 39000, 37800, and 37400. Also, 36800, and 36200.
3. Inspect wiring on Monacillos TC's transient recorder.
    a. Verify wiring for current circuits for terminals 38300 and 36100.
    b. Phase rotation on current channels 36100 (what should be 38300) are incorrect.
4. Inspect wiring on Hato Rey TC's transient recorder.
    a. Line 38900 to Berwind does not show any currents during the event. It is possible that line was open during the event.
5. Perform maintenance procedure to circuit breaker 38550.

### 5.1.6 DC Battery Tests

LUMA will collaborate with PREPA on any corrective actions resulting from the battery tests at the San Juan SP once received from their contractor.

## 5.2 Long-Term Actions

The long-term actions will be planned, scheduled, and tracked to completion aligned with LUMA's Long-Term Investment Plan (LTIP) initiatives and are presented below.

### 5.2.1 System Improvements

As part of LUMA's Area Planning and Substation improvement and expansion plans, the team continues to analyze capacity, redundancy, and reliability factors affecting the transmission system, electrical substation, or switchyard facility. For instance, substation configuration evaluation from straight bus to ring bus or circuit breaker and a half, and additional transformers for the N-1 design compliance. The team will be conducting studies to provide recommendations for a stronger grid, making it less vulnerable to large outages. Among the initiatives under consideration are:

Evaluation of additional transmission lines in the metro area:

- Addition of a third line between San Juan SP and Viaducto TC on an alternate right of way.
- Addition of a direct connection between Palo Seco SP and San Juan SP.
- Addition of a direct connection between Palo Seco SP and Dorado TC.

Additional lines may be identified during the study.

Evaluation of the existing 115 kV bus configurations (i.e., straight bus) in the 115 kV metro area. The studies will initially consider the following substations:

- Viaducto TC
- Monacillos TC
- Hato Rey TC
- Sabana Llana TC.

Any additional mitigation identified in these studies will be included in LUMA's long-term action plan.

### 5.2.2 Data Analysis and Event Reporting

A project to create an event-analysis process is underway. Main items include:

- Improvements to existing event database.
- Revision of the programming of recording devices to fully utilize their capabilities.
- Development of report templates, and
- Process validation against past events and models.

This improved process will help LUMA with the coordination of event analysis and reporting.

As a separated initiative, LUMA is providing certain sites with digital relays and transient recorders with remote access inside a new cyber-secure platform, including Sabana Llana TC amongst others.

### 5.2.3 Protection and Control Systems Renovations

LUMA is advancing on the completion of the protection and control system upgrades in Viaducto TC and Monacillos TC.

Additionally, development of a protection and control renovation plan for Bayamón in coordination with the multiple capital projects underway.

### 5.2.4 Protection and Control Systems Renovations

For the substations not included in the initial round of LUMA's capital projects, LUMA is identifying opportunities for electrical protection, automation, and control (PAC) system upgrades.

The PAC upgrades identify relay changes from electromechanical models to digital models that will provide better coordination of short transmission lines and allow consolidation of devices (such as reclosing, breaker fail, and auxiliary relays) into one microprocessor relay.

### 5.2.5 Relaying Philosophies

LUMA is in the process of continuing the transition to new protection relaying philosophies, according to industry standards and best practices, including revised transmission line-zone protection and revised backup protection for lines and transformers. The changes proposed will provide faster response times of backup protection systems and eliminate chances for miscoordination.

Implementing these steps will help ensure fast clearing of the fault and proper operation of substation equipment in addition to isolating the disturbance should a similar event occur.