Root Cause Assessment of PREPA Outage Event on July 28, 2020

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Prepared for:

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Limitations

Exponent has exercised usual and customary care in the conduct of this assessment. The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations is at the sole risk of the user. Opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation.

The findings presented herein are made to a reasonable degree of engineering certainty. We have endeavored to accurately and completely investigate areas of concern identified during our investigation. If new data becomes available or there are perceived omissions or misstatements in this report, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

Executive Summary

On Tuesday, July 28, 2020, a fault occurring on the PREPA system resulted in a cascading series of events that ultimately interrupted the entire western side and some portions of the eastern side, affecting approximately 789,545 customers. This report referrers to this as the Incident. Exponent was retained by the Energy Bureau of the Puerto Rico Public Regulatory Board ("Energy Bureau") to perform a root cause analysis (RCA) of the Incident.

This analysis identified the following four initiating events (IE) associated with the Incident. These four initiating events formed the basis for the root cause analysis.

IE1: Fault on Transmission Line 50500

IE2: Fault Takes Over 3 Seconds to Clear

IE3: Line 51200 Incorrectly Trips Offline

IE4: Load Shedding is Required After EcoEléctrica Trips Offline

The following root causes have been identified. The first part of the root cause number corresponds to the associated initiating event (e.g., RC-2.X is associated with IE2).

RC1.1. Insufficient Vegetation Management.

RC-2.1. Inadequate Protection System Review Prior to Maintenance.

RC-2.2. Lack of Adequate Backup Protection on Line 50500.

RC-3.1. Protection System Miscoordination.

RC-4.1. Line 51100 Not Sized to Handle Full Fault Duty of EcoEléctrica.

RC-4.2. PREPA Generation System is not N-1 Secure.

In this Incident, many things went wrong. It is possible that all of these failures happening at the same time was coincidence, but more likely that it is an indication of major systemic problems at PREPA involving business issues, system issues, equipment issues, and operational issues.

1. Introduction

On Tuesday, July 28, 2020, a fault occurring on the PREPA system resulted in a cascading series of events that ultimately interrupted the entire western side and some portions of the eastern side, affecting approximately 789,545 customers. This report refers to this as the Incident.

The Incident began at 3:12 pm when a fault occurred on line 50500. Line 50500 is a three-terminal line protected by circuit breakers in the following substations: Mayaguez, Mora, and Cambalache. At Cambalache, circuit breaker 50510 (CB-50510) was under maintenance and CB-0040 was closed (it is normally open).

After the fault occurred, CB-0040 was supposed to open, but did not. The breaker failure backup protection scheme also failed to operate. This caused the line 51100 from EcoEléctrica to Costa Sur to open. Also, due to protection miscoordination, lines 51200 opened at essentially the same time.

The loss of 500 MW from EcoEléctrica also caused a decrease in system frequency. The automatic underfrequency load shed protection scheme activated to avoid a complete system blackout.

A series of transmission line overloads and resulting trips followed, ultimately resulting in interruptions to the entire western side and some portions of the eastern side of the PREPA system.

The fault on line 50500 was cleared after about 3 seconds. Soon afterwards, line 50300 from Aguirre Steam Plant to Costa Sur Steam Plant was overloaded and opened. The lack of generation at Costa Sur caused a partial system collapse.

A more detailed description of the Incident can be found in the report:

Tuesday, July 28, 2020 – 15:12:40
Line 50500 Fault, Automatic Underfrequency Load Shed,
And Overload Disturbance Event Leading to The Collapse of
The West Portion of Puerto Rico's Electrical System

Shavitri E. Vega Blasini, Superintendent
Protection and Control Studies
August 12, 2020

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Figure 1-1. The PREPA 230 kV and 115 kV transmission lines, the location of the fault that initiated the Incident (shown by lightning bolt), and the Western part of the system that was without power after the Incident (boundary shown by thick red line).

2. Problem Statement

The problem statements developed by Exponent for this investigation and RCA are:

1 Both the primary and backup protection systems for the 50500 line at the Cambalache Substation failed to operate after a fault occurred on the 50500 line, resulting in the fault not being cleared for over 3 seconds.

2 A single transmission line fault, which would normally be expected to result in no interruptions to customers, ultimately resulted in the interruption of the entire western side and some portions of the eastern side of the PREPA system.

The focus of the first problem statement is directed at determining the root causes of why the transmission line primary and secondary protection systems did not operate properly. If they had operated properly to quickly clear the fault on the 50500 line, it is likely that there would have been minimal impact to customers.

The focus of the second problem statement is directed at determining the root causes of why the failure of a primary and secondary transmission protection scheme led to widespread outages on the PREPA system.

While these problem statements apply specifically to the Incident, they generally apply to potential similar situations that may occur at PREPA in the future.

3. Approach

The approach used for this investigation and root cause analysis (RCA) is summarized herein to provide context for the discussion and results presented in the subsequent sections of this report. From an overall causal analysis perspective, the three main types of barriers to the prevention of an unwanted event (Figure 3-1) are:

- Physical Controls
- Processes and Procedures
- Management Policies and Organization

Causes of major incidents or losses typically involve latent conditions[1] related to management policies and organizational interfaces that inadvertently degrade the effectiveness of the various barriers in place. For this reason, all types of barriers are reviewed.

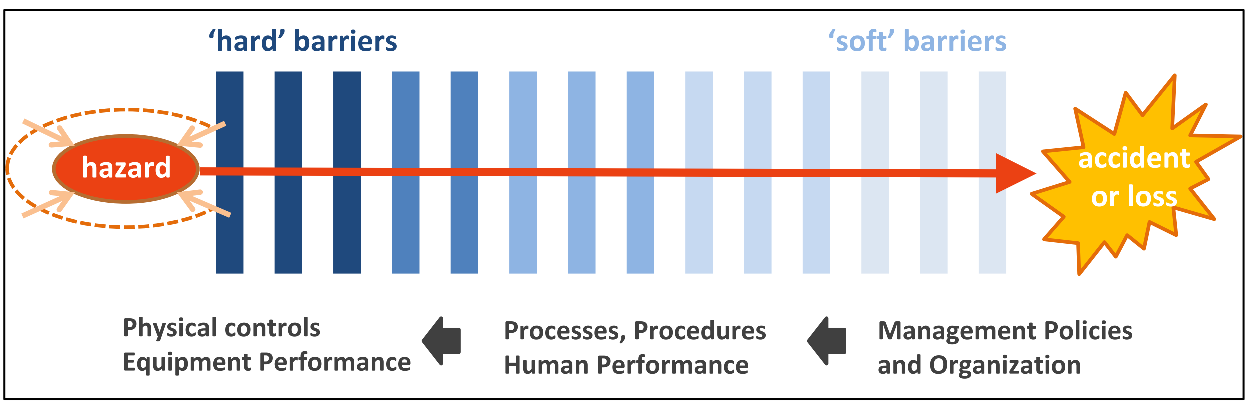

Figure 3-1. Root Causes of Unwanted Events.

[1] Latent conditions are hidden deficiencies in management control processes or values creating workplace conditions that can provoke errors and degrade the integrity of defenses (US Department of Energy, Human Performance Handbook, Human Performance Improvement Concepts and Principles, 2007).

The approach used in this investigation shall consist of the following five steps:

Data Collection. Data collection will be performed through a review of related event documents, interviews and discussions with personnel involved in the event and other subject matter experts. These activities can valuable insights into the organization, as well as formal and informal processes by which related work is performed.

Reconstruction of Event Timeline. As a result of the data collection activities, an incident timeline will be constructed to provide background and understanding of the conditions that existed prior to the incident and activities performed during the processes involved in the event. Furthermore, the timeline will identify when various activities occurred and which organization was responsible for these activities. This review will provided a basis for identifying actions or tasks that did not follow the prescribed "as-required" process and areas where those processes may be deficient. The outcome of this effort will be a list of "initiating events" that will be used as the starting point for the RCA. "Initiating events" are defined as those issues that represent conditions, errors or non-compliance with required practices and processes.

Root Cause Analysis. The RCA will be performed in a structured sequence of steps that lead to identification of the root and contributing causes. Analyses will be supported by the previously described data collection activities, including insights. The RCA tools that will be used in this investigation will be:

a. Event Timeline Analysis – This tool will be used to identify the initiating events of the causal analysis. The time of each event that physically occurred and events or behaviors that either didn't happen or should have happened will be noted.

b. Events and Causal Factors Analysis (ECFA) – This tool will be used to identify potential systemic incident causes (i.e., management policies and organization) for each initiating event. It will involve repeatedly asking why the event or pre-condition existed in order to identify the underlying causes.

c. Human Factor Analysis and Classification System (HFACS) Analysis – This tool will be used as a supplementary causal analysis tool to identify and classify human-and-organizational-factor related causes. It will involve reviewing a predefined list of human and organizational pre-conditions and determining those that apply to the incident based on the data collection and experience of the assessment team. The results will be used to inform the determination of the initiating events and causes in the causal chains for human performance-related activities.

d. Causal Factor Unit Analysis – This step will involve a detailed evaluation of each cause identified in the ECFA that will be used to determine the root causes and contributing causes of the incident. It will involve assessing the degree to which each condition that contributed to the incident is within management's control to change and whether its removal would have prevented the occurrence of the problem. Those causes that meet these criteria are the root causes of the incident.

3 Investigation and Analysis

The investigation and analysis tasks include records reviews and responses to requests-for-information that were submitted to PREPA. The results and observations from the activities are described in this section.

Timeline

On Tuesday, July 28, 2020, the PREPA electrical system was in the normal operation state with the following contingencies being in place as a result of the September 2017 hurricanes, the January 2020 earthquakes and general system deterioration that has occurred over time.

- All generation from Costa Sur Steam Plant was out of service due to earthquake damage.
- The electrical system was receiving approximately 500 MW from the EcoEléctrica Plant via line 51100 from EcoEléctrica to Costa Sur.

Three terminal line 50500 from Cambalache Gas Plant to Mora Transmission Center and Mayagüez Transmission Center was energized. Breakers 50580-0090 at Mayagüez Transmission Center and 50540 at Mora Transmission Center, were closed. At the Cambalache terminal, breaker 0040 was closed and breaker 50510 was under maintenance with the auxiliary breakers A and B open and the direct current source (DC) to the control was de-energized. See Figure 3-1.

At 15:12:40.960, a fault at line 50500, occurred and was sensed by the relays and the transient fault recorders (tree branches were found by field personnel in the area matching the fault location and description reported by the relays).

Breakers 50580-0090 at Mayagüez T.C. opened to isolate the fault in 0.067 seconds. This terminal reported 3,000 amps per phase and fault location of 15.97 miles. Breaker 50540 at Mora T.C. opened to isolate the fault current from that terminal in 0.3 seconds.

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Figure 3-1. Cambalache Substation One Line Diagram

Breaker 0040 at Cambalache did not open and the associated breaker failure protection was not operational, both due to no DC power, causing a back-up operation at the remote 230 kV terminals (from Cambalache) to clear the fault for a total of 3.14 seconds. Remote Zone 3 back up protection for Cambalache line 50500 occurred as follows:

- Cambalache to Costa Sur Line 51200, 51220-0032 breakers opened in 1.415 seconds.
- Cambalache to Manatí TC Line 50100, 50110-50214 breakers opened in 3.04 seconds.
- Cambalache 230/115 kV transformer, breaker 41320 opened in 3.14 seconds.

On the PREPA system, 230 kV short circuit currents are low in magnitude. Therefore, overcurrent back up protection coordination is slow for fault clearing at this voltage level and is typically used only as a third or fourth contingency, as was the case during this Incident. For this reason, redundant primary protection (e.g., line differential) is typically used.

Before the fault was completely cleared the following events occurred, which resulted in the interruption of the entire western side and some portions of the eastern side of the PREPA system, affecting approximately 789,545 customers.

Line 51100 from EcoEléctrica to Costa Sur S.P. tripped as a result of directional time overcurrent back up protection. The relays at EcoEléctrica show that the current from this terminal (2,000 amps) was greater than the current at line 51200 from Costa Sur to Cambalache (1,450 amps). The lack of generation at Costa Sur resulted in a greater short circuit current from EcoEléctrica that was divided between lines 51200 and 50200 from Costa Sur to Cambalache and Manatí, respectively. This situation caused a protection mis-coordination between lines 51200 and 51100 opening breakers 51110-0030 at EcoEléctrica 0.063 seconds after breakers 51220-0032 at Costa Sur opened to remotely clear the fault at line 50500.

With the outage of line 51100, the system lost approximately 500 MW from EcoEléctrica and the system frequency dropped to 58.46 Hz. An automatic load shed event then occurred, dropping load to stabilize the frequency of the system. The system frequency recovered after the automatic load shedding event.

Breakers 50230-50940 in Bayamón TC opened line 50200 from Bayamón T.C. to Manatí T.C. A fixed time Zone 3 protection scheme operation is reported by the relay two seconds after the beginning of the fault at line 50500.

Breaker 36180 opened line 36100 from Caná Sect. to Barrio Piñas G.I.S. 3.1 seconds after the fault at line 50500 occurred. Line 36100 protection is set for 460 amps, and the relay reported an overload trip of the line with 702 amperes.

At 15:17:24.323, the remaining transmission line feed from Bayamón to Manatí, line 37400, was interrupted with a fault due to a fallen conductor at the line segment from Bayamón TC to Hato Tejas TC. This situation imposed additional stress to the electrical system. After this event, the System remained with the north-western and south-western parts of the island fed from 230 kV lines 50200 Costa Sur - Manatí and 50400 Costa Sur - Mayaguez, and 115 kV line 37100 from Costa Sur to Guánica-San Germán.

At 15:24:12.538 (11:28.438 minutes after the line 50500 fault was cleared) line 50300 from Aguirre Steam Plant to Costa Sur Steam Plant was overloaded and tripped. After this, the system frequency increased to 61.2 Hertz. The lack of generation at Costa Sur Steam Plant prevented the system from recovering from the loss of line 50300.

Additionally, at 15:27:56, after an overload trip at 15:17:27.956 form line 10700, 38kV breaker 10720 at Bayamón Pueblo Sectionalizer was closed to restore the system. However, breaker 10720 was in a damaged condition when it was closed, resulting in a bus fault.

After these severe disturbances, only portions of the eastern side of the island remained in service due to the previous load shed event from EcoEléctrica.

Initiating Events

The timeline indicates the following four initiating events (IE) that contributed to the widespread outage on the PREPA System:

- **IE1: Fault on Transmission Line 50500**: The Incident began when a fault occurred on transmission line 50500, resulting in fault currents of approximately 3000 amps (Fault). This Fault was most likely due to vegetation contact. Tree branches were found by field personnel in the area matching the fault location reported by the relays.

- **IE2: Fault Takes Over 3 Seconds to Clear**: The primary protection system of the 50500 line requires breakers to trip at the Mayagüez, Mora, and Cambalache substations. The trips at Mayagüez and Mora occurred in 0.067 seconds and 0.3 seconds, respectively. The primary and backup protection schemes at Cambalache both failed to operate, resulting in the fault being cleared by Zone 3 protection at the remote 230 kV terminals of Cambalache after 3.14 seconds.

- **IE3: Line 51200 Incorrectly Trips Offline:** The Fault resulted in high currents flowing out of EcoEléctrica through line 51100. Normally a line dedicated to a generation facility (like line 51100 is for EcoEléctrica) will be sized to handle the short circuit duty of the generation facility. In this case, the short circuit contribution from EcoEléctrica was higher than normal due to the Costa Sur generation facility being offline. This resulted in (a) line 51100 being unable to handle the short circuit current; and (a) protection miscoordination between line 51100 and line 51200. In a normal situation, neither line should trip for a fault on Line 50500. If line 51100 were simply undersized, only line 51100 should trip. In this case, both lines tripped.

- **IE4: Load Shedding is Required After EcoEléctrica Trips Offline:** The tripping of line 51100 resulted in the loss of approximately 500 MW from EcoEléctrica. As a result, the system frequency dropped to 58.46 Hz. In order to prevent a total system collapse, a load shedding scheme was automatically initiated.

These four initiating events formed the basis for the root cause analysis.

4 Root Cause Analysis

There is a single root cause associated with IE1: Fault on Transmission Line 50500.

RC1.1. Insufficient Vegetation Management. Vegetation-caused faults on 230 kV transmission lines should be rare. Based on the PREPA responses, it appears that PREPA relies solely on reactive hot spot trimming, where helicopters patrol the lines every three months and identify areas that require vegetation management. Typical vegetation management programs for transmission lines are much more extensive and include cycle trimming, aerial and/or ground-based patrols, and the use of herbicides. In its response, PREPA states, “it can be observed that the reported vegetation deficiencies were not worked out before the event.

There are two root causes associated with IE2: Fault Takes Over 3 Seconds to Clear.

RC-2.1. Inadequate Protection System Review Prior to Maintenance. As part of the safety procedure for performing maintenance on breaker 50510, switches A and B were open and the direct current source (DC) to the control was de-energized. Cambalache Gas Plant was commissioned by PREPA during the 1990’s and the design at this installation is not typical. Among the four relays composing the protection of line 50500 at the Cambalache terminal, the DC circuit of two of the relays were wired with the control of breaker 50510 and two relays with the control of breaker 0040. The standard design at PREPA’s facilities requires separate DC elements for breaker control and the protection relays for maintenance and operational purposes. In addition, the two relays related to the control DC at breaker 0040 were out of service due to previous damage and obsolescence. For this reason, the line protection at this terminal was performed solely by the two relays fed from the control DC of breaker 50510. When the DC for the control of breaker 50510 was de-energized for safety by the field personnel, line 50500 at Cambalache was left inadvertently without protection.

PREPA states that "the drawings identifying all the equipment connected to the DC source that was going to be disconnected were not verified." Verification should have occurred as this was (a) a non-standard design, and (b) a situation where two relays were out of service at the substation. In this type of situation, a full review by the protection group would typically be required. PREPA also states, "Normally, if there is an abnormal operating condition, there is a sign indicating it so that proper precautions are taken. In this case, there was no sign." It appears that the maintenance workers assumed that the lack of a sign meant that there were no special considerations for this particular maintenance activity. It should not be the responsibility of maintenance workers to identify issues such as non-standard substation designs and the fact that certain relays in the substation are not operational.

RC-2.2. Lack of Adequate Backup Protection on Line 50500. It is unacceptable for backup protection to require 3 seconds to operate. In this case, the primary and secondary carrier protection for Line 50500 were not operational and a Zone 3 protection scheme had to operate. Had carrier protection been operational, the backup protection would have operated much sooner and likely would have resulted in a very minor event.

In addition, there were two backup relays associated with Line 50500 that have been out of service since July of 2018, with no plans to fix or replace them. PREPA states that replacement is not necessary since there is already "redundant protection," but it also states that "An upgrade will be done in the future, replacing those relays with updated relays." Had these relays been previously replaced, they would not have been impacted by the lack of DC supply and the Incident would have been avoided.

There is one root cause associated with IE3: Line 51200 Incorrectly Trips Offline.

RC-3.1. Protection System Miscoordination. Line 51200 should not have tripped at the same time as Line 51100. Had proper protection coordination been in place, it is unlikely that Line 51200 would have tripped at all. PREPA explains as follows, "The lack of generation at Costa Sur resulted in a greater short circuit current from EcoEléctrica that was divided between lines 51200 and 50200 from Costa Sur to

Cambalache and Manatí. This situation caused a protection miscoordination between lines 51200 and 51100."

It is typical for utilities to perform dynamic stability studies for all N-1 conditions, including when major generation facilities are offline. It appears that PREPA does not do this, and also did not update its short circuit and protection coordination studies when Costa Sur was taken out of service.

PREPA states that after the earthquakes NYPA agreed to perform coordination studies and determine appropriate protection settings. It is not clear if this was for normal or emergency conditions. PREPA goes on to state that when under emergency conditions, protection settings are supposed to be evaluated and updated, but "Since the hurricanes, Irma and Maria, this process has not been followed."

There are two root causes associated with IE4: Load Shedding is Required After EcoEléctrica Trips Offline.

RC-4.1. Line 51100 Not Sized to Handle Full Fault Duty of EcoEléctrica. The fault on Line 50500 resulted in EcoEléctrica injecting about 2000 amps of fault current into Line 51100. PREPA states, "The lack of generation at Costa Sur resulted in a greater short circuit current from EcoEléctrica." However, Line 51100 should have been sized to handle the full fault duty of EcoEléctrica, as there will always be situations in which Costa Sur will have to be taken offline for maintenance activities. If Line 51100 had not tripped, the system frequency drop would not have occurred and the underfrequency load shedding would not have been needed.

RC-4.2. PREPA Generation System is not N-1 Secure. When EcoEléctrica tripped offline, it caused the system frequency to drop significantly enough to require automatic load shedding. At a bare minimum, a utility system should be able to withstand the loss of its largest generation station without interrupting any customers. This is referred to as being "N-1 Secure" because if there are N generation stations the system can operate at full capacity with only N-1 generation stations being online. One could argue that the

PREPA system was already in an N-1 condition due to the fact that the Costa Sur Steam Plant was out of service due to earthquake damage since service since January 7, 2020. However, the Incident occurred 7 months later and it is not acceptable to have a major utility system in an insecure state for this length of time.

5 Conclusions

The Incident had four initiating events: a fault on a transmission line, a very slow clearing time of the fault, a transmission line that incorrectly trips offline, and the need for underfrequency load shedding. It is rare to have so many initiating events related to a power system outage event. For most utilities, a fault on a transmission line is simply cleared by the protection system and no customers are impacted whatsoever. In this case, a fault on a transmission line interrupted the entire western side of the PREPA system and some portions of the eastern side, affecting approximately 789,545 customers.

For this Incident, each initiating event was avoidable. The fault on the transmission system could have been avoided with a more robust vegetation management program. The slow clearing time could have been avoided by requiring protection system reviews prior to certain maintenance activities and/or having adequate backup protection in place. The incorrect tripping of a transmission line could have been avoided by having proper protection system coordination. Last, underfrequency load shedding could have been avoided by, in this case, properly sizing transmission lines to handle worst-case fault duty, and more generally, having a generation system that N-1 secure.

In this Incident, many things went wrong. A typical outage investigation will involve a few things that went wrong, but there were many more in this case. It is possible that all of these failures happening at the same time was coincidence, but more likely that it is an indication of major systemic problems at PREPA involving budgets, inspections, maintenance, staffing, compliance with standards and business processes, a deteriorated and under-maintained system, and possibly other aspects.