

## GLOSSARY

**Breaker Failure Relay:** The breaker failure relays are intended to act as secondary protection for the primary protection relays. (The primary protection relays operate the breakers in the event of a system fault.) In normal operation, the breaker failure relay asserts an additional trip signal (re-trip) to the breaker as soon as it receives the signal from the primary protection relay. This is intended to back-up the primary protection relay in case the output from the primary relay did not initiate the breaker trip operation. If the retrip is successful, a larger outage opening of backup breakers is avoided. If the retrip is unsuccessful the breaker failure relay will open all of the adjoining, upstream breakers to clear the fault. The breaker failure relay only opens these upstream breakers if the current in the primary breaker persists for a pre-set period of time, indicating the primary breaker is malfunctioning. Tripping upstream breakers prevents the continued fault from causing further damage to the system.

**False Trip:** This defines the operation of the breaker failure relay to actuate without a signal from the primary protection relay.

**Hetch Hetchy:** San Francisco water district.

**INPO:** Institute of Nuclear Power Operators

**IRIG:** This is a time system that records and synchronizes the times recorded on the relays.

**MUNI:** San Francisco municipal transit system

**RAS:** Remedial Action Scheme is a control system that is used to mitigate outages and maintain system stability.

**RS232:** Serial data port that allows for connections of the data devices per EIA standards.

**Re-trip:** The re-trip is a function of the breaker failure relays to provide an additional signal to trip the circuit breakers when the breaker failure relay receives an input signal from the primary protection relays.

**SCADA:** Supervisory Control and Data Acquisition system that acquires data for evaluation and control of the substation and system.

**Transient:** This is a disturbance on the power system that produces voltage or current changes in the system.

**AC:** Alternating current (AC) is the electric current whose magnitude and direction vary cyclically with time.

**DC**: Direct current (DC) is the constant flow of electric charge with constant polarity. The electric charges flow in the same direction, distinguishing it from alternating current (AC).

## EXECUTIVE SUMMARY

### Event Description

On July 24, 2007, starting at 1:46 pm, multiple circuit breakers operated (opened and reclosed) at the Martin substation five times over a period of thirty-five minutes. The individual events consisted of the simultaneous actuation of multiple breaker failure relays that tripped the associated circuit breakers. These events resulted in momentary interruptions of service to 26,899 customers fed from the Embarcadero Substation (including Substation J) and in sustained interruption of service to 27,132 customers fed from Martin Transformer Bank #1.

Immediately following the incident, the Utility retained forensic consultant Exponent to assist in the investigation of the incident, root cause analysis, and development of a corrective action plan.

### Findings

The combined cause of the false operation of twelve breaker failure relays was the incorrect wiring of a tester that was being used to test a temporary circuit breaker coupled with the unusual susceptibility of these particular relays to false signals. The wiring error subjected the breaker failure relay DC power supply to a 60Hz voltage signal and exposed the relays' unusual susceptibility to this false signal.

On the date of the incident, crews were testing a temporary circuit breaker and these tests had the potential to introduce AC voltage into the DC system. The DC power source for the spare circuit breaker test was in the 230kV control building which housed the subject breaker failure relays. Test records from the temporary circuit breaker test equipment, interviews with site personnel, and field testing demonstrated that an incorrect testing configuration reproduced the July 24 event records.

Given the amount of data generated by breaker failure relays, the lack of a clear, immediately identified cause, and other devices that had to be reviewed and examined, the investigation was complex and required a process of elimination in order to determine the cause of the tripping of the breaker failure relays. Throughout this process of elimination, three different teams of interviewers went to the Martin Substation and spoke with various employees working at the yard on the day of the incident. It was not until those involved in this investigation had reviewed extensive data and eliminated various potential causes for the tripping that the team focused on the testing of the circuit breakers as a possible trigger for the event. Thereafter, the team was able to ask more probing and relevant questions of those conducting the circuit testing on July 24<sup>th</sup> to determine the triggering cause for the event.

No one on-site at Martin substation was aware that the circuit testing was related to the tripping and momentary outages. This is because the equipment was being tested in an area where personnel conducting the testing were unaware that the breaker failure relays were operating, causing power disruption.

The breaker failure relays involved in the incident are newer units containing different internal components than the units received before November 2004. These newer breaker failure relays, unlike the older units used in the PG&E system, are susceptible to false signals. The newer units can be modified to correct the susceptibility. There are approximately 140 newer units that require modification.

No amount of noise immunity protection will render all relays and breakers safe from sustained AC transients across the DC power supply. Therefore, relay and breaker testers and procedures will be reviewed to reduce the probability that technician errors will initiate an undesired sequence of events.

# REPORT

## Background

PG&E's power delivery system equipment is protected from serious damage through the use of circuit breakers, which turn equipment off (interrupt current) in the event there is a fault (short circuit) in the system. Each circuit breaker in PG&E's high voltage transmission network is operated by a number of microprocessor-based devices called "relays." In the event of a fault within the equipment protected by a given circuit breaker, these relays sense the fault and send a signal to open the circuit breaker.

Each transmission circuit breaker is associated with another microprocessor-based device called a "breaker failure relay (BFR)." The BFR performs two functions (see Figure 3):

1. It sends a redundant trip signal (called a "re-trip") to trip the circuit breaker immediately.
2. If the circuit breaker fails to operate after a preset time, the BFR operates other breakers adjacent to the failed circuit breaker; thus providing backup protection and assuring faults are cleared.

On July 24, 2007, starting at 1:46 pm, multiple breakers operated (opened and reclosed) at Martin Substation five times over a period of thirty-five minutes. This resulted in momentary interruption of service to 26,899 customers fed from the Embarcadero Substation (including Substation J) and sustained interruption of service to 27,132 customers fed from Martin transformer bank #1 (see Figure 1). The individual events consisted of the actuation of multiple breaker failure relays that initiated trips of the associated circuit breakers.

Between the first and second Martin events (see Figure 1), a network transformer failed at Mission and First Streets in San Francisco. The transformer failure did not result in an interruption of service to customers. There is a separate investigation into the root cause for the network transformer failure.

The sequence of events ended at approximately 2:25 pm when the Martin substation was returned to service.

Pacific Gas and Electric, with the assistance of retained forensic consultant Exponent, immediately began an analysis to determine the cause of the failure and to implement short-term measures to prevent recurrence. In parallel, long-term corrective action plans were developed. Additionally, PG&E examined the transmission system to identify the potential for similar conditions and to develop a plan of action to address any such conditions.

## **Immediate Actions**

The following actions were taken immediately after the incident:

- Data was collected from the 230 kV control room components, including protection relays, breaker failure relays, SCADA, RAS, and sequence of events recorders.

The data review from these components indicated that the primary protection relays did not initiate a trip signal to the circuit breakers or to the breaker failure relays. The data review also indicated that the breaker failure relays did receive an initiation signal. Therefore, the breaker failure relays became a major component in the investigation. The review indicated that:

- Twelve breaker failure relays showed that each relay received input signals (on input 3) and opened the associated breakers almost simultaneously (see Figure 2).
  - Two breakers were tripped due to power failure (loss of voltage on both sides of the breaker), which is an expected event since this is how the system is designed to operate (see Figure 2).
  - One breaker did not operate (see Figure 2).
  - Breakers reclosed normally by automatic controls, as designed.
  - The trip and reclose cycle occurred five times over an approximate thirty-five minute period of time.
  - There were no other relays that operated prior to the event.
- Employees at Martin Substation were interviewed and it was learned that:

No unusual activities were underway at the time of the incident. The investigative team learned that there was testing of a temporary circuit breaker being conducted around the time of the event. The testing was conducted in an area removed from the control building. [The temporary circuit breaker was located next to the 115kV switchyard, and out of the line of site of the 230kV switchyard where the circuit breaker trips occurred. The 230kV control building and other temporary trailers were between the temporary circuit breaker and the 230kV switchyard.] The initial review indicated that the recorded testing times did not correspond to the event times, and that the location of the temporary circuit breaker was remote from the circuit breakers that tripped. As a result, investigators did not focus on the testing until significant data had been reviewed and other possible triggers eliminated. Later, as discussed below, investigators found that there were failed tests that were not recorded or reflected in the initial data reviewed.

- System operators were interviewed.

A discussion with system operators and a review of system logs indicated that there was no evidence of a system transient or of fault from the data recordings; of a ground fault from data recordings; or of operator action to cause these events (based on review of the operator log, switch schedule, or data records).

Based on the data, it appeared that the breaker failure relays had operated absent a valid signal (“false tripping”). In the case of false operation of the breaker failure relays, no breakers failed to operate, so no tripping of the backup breakers was warranted.

PG&E implemented the following immediate corrective actions on July 24, 2007.

- Disabled the reclosing function for each breaker.
- Disabled the breaker failure relays for each breaker.
- Placed SCADA on local control with stations manned.
- Contacted the relay manufacturer to obtain technical assistance.

The simultaneous false tripping of more than one breaker failure relay indicated that there was a common link. Several common links were identified as possible causes or contributing factors in the event including: (1) DC power supply since all relays were on the same battery system; and (2) Station ground grid since all of the relay chassis are connected to the station ground.

There were two other possible common links identified, but ruled out for immediate evaluation. The IRIG clock timing system and the RS232 remote communication system were links that were common to the breaker failure relays. However, review at the site indicated that the IRIG and RS232 systems were not connected to all of the breaker failure relays that falsely tripped, so these were eliminated.

PG&E also reviewed prior events looking for possible similarities to the present event. Two previous false tripping events of the breaker failure relays at the Martin substation were identified. The first occurrence was March 14, 2007. This event involved four breaker failure relays, which indicated a short pulse on the breaker failure relay input 3 terminals. The apparent cause of this event was determined to be the operation of a SCADA switch, which caused contact between a wire lug connector at 125V DC potential and grounded mounting bolts. This defective SCADA switch was replaced. The second occurrence was April 18, 2007. This event involved one breaker failure relay. There has been no known cause identified for this event. The relay was replaced and sent to the manufacturer for examination and analysis. The manufacturer has not provided an update on its investigation.

Based on the initial analysis of the breaker failure relay configuration, the following additional actions were implemented on July 27, 2007 to add security to the breaker failure relay scheme to both reduce the risk of a similar event and mitigate the consequences of such an event:

- The re-trip function from the breaker failure relay was disabled.
- The overcurrent setting on the breaker failure relay was changed to a value greater than load current so that it would only allow breaker failure trip if there was an overcurrent (fault current) through the breaker.
- A resistor was installed across the breaker failure initiation input to reduce the relay's sensitivity to potential noise or transient disturbances. (This action was added based on the initial output from the root cause analysis simulation. This simulation is discussed in the Section 3.)

### **Data Review**

Exponent's initial data review indicated that the breaker failure relays tripped in response to a signal received through the input 3 terminal. The relays are designed to respond to a signal that is 80V DC or higher. This review indicated that a disturbance on the common DC power supply would induce a false trip of the breaker failure relays.

### **Evaluation of Breaker Failure Relay Performance**

The breaker failure relay circuitry was reviewed and a model developed for mathematical simulation of the relay with various input and output components. The initial simulation indicated that the breaker failure relays could develop a "static" voltage on the input 3 terminals. PG&E took field measurements of the incident relays, which showed the presence of "static" voltage ranging from approximately 35 to 70V DC - a significant percentage of the 80 volts required to actuate the relays. Thus, the relays were found to be predisposed to false tripping from transients.

Simulations were performed on the breaker relay circuits with inputs through the DC power supply. The simulations indicated that:

- A DC pulse, such as could arise from an accidental connection of the 125V DC station battery to ground or large voltage swings of the battery potential relative to ground, could cause false tripping of the breaker failure relays. This type of pulse reproduced the breaker failure relay data from the March and possibly April events, but did not reproduce the breaker failure relay data from the July 24 event.
- A 60 Hz AC voltage applied between the 125 DC station battery to ground could cause false tripping of the breaker failure relays and would reproduce the breaker failure relay data from the July 24 event.

Based on this initial analysis and simulation, it was decided to add a 47-kOhm resistor across the breaker failure initiate input (Input 3) of the breaker failure relays to reduce the "static" voltage and to desensitize the relays to avoid false tripping of the relays resulting from accidental grounding of the batteries. Simulations of this modified relay

configuration indicated that the relay would not actuate the breaker failure relays under a DC pulse and it reduced the probability for actuation of the breaker failure relays in case of a 60 Hz AC voltage applied to the poles of the 125V DC battery.

During the July 24 event, there were two breaker failure relays that did not false trip. When field testing of these relays was performed, they showed almost no “static” voltage ( $< 2V$ ). These test results indicated that there may be a difference in the design of the breaker failure relays depending upon manufacturing date. Therefore, it was decided to obtain an older breaker failure relay from the Moraga station and to include this in the testing program. Field testing of this Moraga breaker failure relay also showed no presence of “static” voltage.

A test program was developed by Exponent and provided the following results (See Figure 4):

- The testing validated the simulation model results, which provided some assurance that future simulation results would also be reliable and likely reduce the need for testing.
- There is a difference in performance between the older breaker failure relays and the newer units that false tripped. This observation indicates that there is a circuitry change in the newer version of the breaker relay.
- The newer relay (unmodified) is susceptible to false trip and re-trip under both the DC pulse and AC input stimuli.
- The newer relay (modified with the 47 kOhm resistor) is not susceptible to false tripping due to the DC pulse stimuli. This relay is also not susceptible to false tripping due to AC input if the input contact recognition delay is increased to 12 millisecond (from current 8 millisecond setting).
- The older model of the original breaker failure relay is not susceptible to false tripping due to either type of stimuli.
- The replacement relay from another manufacturer is not susceptible to the DC pulse; however, at AC input over 76V, this relay is also susceptible to false tripping.

These test results show that the newer breaker failure relays (modified with the 47 kOhm resistor and an increase in input contact recognition delay to 12 milliseconds) provide a relay behavior consistent with the older design. The older breaker failure relays exhibit good immunity to the tested stimuli. The modification of the new relay therefore returns the system to be consistent with the old relay design such that an equivalent level of immunity to false tripping is achieved when it was tested with the described transient events from grounding of the station battery or from accidental connection of an AC source to the station battery.

The component evaluation did not identify any other possible cause for false tripping of the breaker failure relays beyond the identified ground contact to the 125V battery or its connection to a 60 Hz AC source. This information therefore focused the investigation of the initiating event on potential causes of AC input onto the station battery to reproduce the observed relay response of July 24.

### **The Triggering Event**

While the review of the breaker failure relay performance provided information to allow modifications to the newer relays such that they demonstrated susceptibility comparable to the older units, an investigation to determine the initiating event was also performed. Based on a review of the system design and the available event data, four potential common links, which could conceivably cause false tripping, were identified:

- DC power supply disturbance
- RS232 communication system
- IRIG timing system
- Station ground grid

The RS232 and IRIG were not connected to all of the affected breaker failure relays and were therefore eliminated. No scenario involving the grounding grid was found that was expected to induce false tripping. The DC power supply therefore became the focus of the investigation. Based on the breaker failure relay testing, an AC voltage on the DC supply was the only transient that reproduced the known July 24 relay behavior. The review of initiating events therefore focused primarily on conditions or actions that may have introduced AC voltage into the DC system. Figure 5 presents a flowchart showing the various causes considered and the status of the review for each possible cause.

There are four types of initiating events that were reviewed for the introduction of potential AC input into the station battery:

- DC power supply malfunction
- Site activities (construction and maintenance)
- Operating (system) activities
- External causes

### **Site Activities**

On the date of the incident, crews were testing a temporary circuit breaker and these tests had the potential to introduce AC voltage into the DC system. The DC power source for the spare circuit breaker test was in the 230kV control building which housed the breaker failure relays. Further investigation included the following:

- Initial site interviews with personnel performing the testing that did not identify any anomalies during the tests. Also, the times of the temporary circuit breaker tests (recorded internally by the test equipment) did not appear to match the times of the five circuit breaker events.

- Laboratory testing of the CT-7000 circuit breaker testing equipment was then performed to determine whether it could introduce AC voltage into the DC system (through an internal short circuit). The laboratory testing indicated that the CT-7000 equipment was performing according to its design. However, further testing of the lead connections showed that a mistake in connection could introduce AC current into the DC and could reproduce the event.
- A review of the temporary circuit breaker testing stored records from the CT-7000 indicated that the July 24 incident occurred while testing was being performed since the first test was recorded at 1:21 pm and the last test was recorded at 2:55 pm. There were also a few tests at various times in between but the timing of the recorded tests did not correlate with the event times.
- After additional questioning of personnel at the site, investigators learned that there had been a few failed tests that were not saved (recorded) on the testing device. Typically, test records for failed tests are not saved unless the operator of the tests opts to do so. In this case, the operator did not opt to do so. Those involved in the testing reported that the circuit breaker did not operate during these test, but that there was a noise heard emanating from the close coil. Additional test records (paper strip recordings, not stored records) were recovered for three failed tests each occurring at approximately 52 seconds after the time of one of the Martin events (events 2, 4 and 5) Additional testing of the CT-7000 testing device indicated that its internal clock was approximately 52 second ahead of the satellite clock used to time the July 24 event. Therefore, the three failed tests occurred at the times of three of the circuit breaker events.
- Testing of the temporary circuit breakers was performed to determine if the July 24 event could be reproduced. Tests were performed on two consecutive nights revealed:
  - Proper operation of test equipment was observed with correct wiring.
  - The test equipment was intentionally set up with an incorrect connection. Specifically, the connection was made to a terminal with AC power rather than the correct connection to DC power.
  - The July 24 event was reproduced four times. The breaker failure relays (without resistors) false tripped and the data recordings from the relays and circuit breaker test equipment matched the data from the July 24 event. There was also a noise heard to emanate from the close coil, and the test failed.

Based on the data collected, mathematical simulations, testing performed, and the timing of test records, the triggering event of the false tripping of the breaker failure relays was the incorrect wiring of a breaker tester that was being used to perform testing on a temporary circuit breaker.

### **Review of Prior Events**

There have been two previous false tripping events with the breaker failure relays at the Martin substation. The first occurrence was March 14, 2007. This event involved four breakers, which showed that a short pulse resulted in the breaker trip output. The apparent cause of this event is believed to be the operation of a SCADA switch, which caused contact between a wire lug connector at 125V dc potential and grounded mounting bolts. This switch was replaced. The second occurrence was April 18, 2007. This event involved one breaker failure relay and there was no cause identified for this event. The relay involved in this event was removed and sent to the manufacturer for review.

A review of the data from these events indicated that the input to the breaker trip relays was of short duration. The data from the July 24 event indicated that the input was of long duration so that the July 24 event was different than the previous two events. However, testing of the newer breaker failure relays indicated that they would have been susceptible to the DC voltage pulses, which was confirmed through the testing performed after the July 24 event.

We did not uncover any relevant information relating to this type of relay failure from a literature search. The INPO operating experience database, however, notes that human error may cause false tripping of breaker failure relays.

### **Review of System**

Since a contributing cause was the unusual susceptibility of these newer breaker failure relays, PG&E identified the location and number of these like-relays in service. There are approximately 140 of these newer breaker failure relays supplied by the manufacturer and presumed to be in use throughout the PG&E system.

In reviewing the events and data at Martin from July 24, there were 12 breaker failure relays that false tripped and two breakers failure relays that operated properly. The field and laboratory testing indicated the presence of “static” voltage in the relays that false tripped. Field tests were conducted on the breaker failure relays that operated properly to check for the presence of “static” voltage. The field tests indicated very low (< 2V) “static” voltages on these relays.

An additional relay, which had previously been removed from service in the Moraga substation, was field tested and no “static” voltage buildup was found when it was placed in a circuit similar to the Martin installation. This relay (of the same manufacture date range as the two breakers that did not mis-operate) was sent to the Exponent laboratories for testing. Exponent testing revealed that this relay, like the two that did not false trip on July 24, 2007, was not susceptible to false tripping due to a DC pulse or an applied AC voltage.

Information relating to the differences found in the relays was sent to the manufacturer. The manufacturer confirmed that relays after a specific serial number (more recent relays) had different circuitry than relays manufactured earlier. PG&E was not aware of

the internal circuitry change in these breaker failure relays. Relays from this manufacturer have been in use throughout PG&E for many years. Additional field tests verified that there was a consistent difference of “static” voltage for relays with lower serial numbers when compared with those with higher serial numbers.

The affected breaker failure relays at the Martin, San Mateo, and Jefferson substations have been modified with resistors as described in the Martin substation short-term corrective actions. PG&E has developed a plan for the modification of all of the susceptible breaker failure relays. The plan includes the following:

- Addition of resistors across the breaker failure relays input terminals
- Removal of unused inputs from the relay logic
- Extension of the contact recognition time from 8 milliseconds to 12 milliseconds

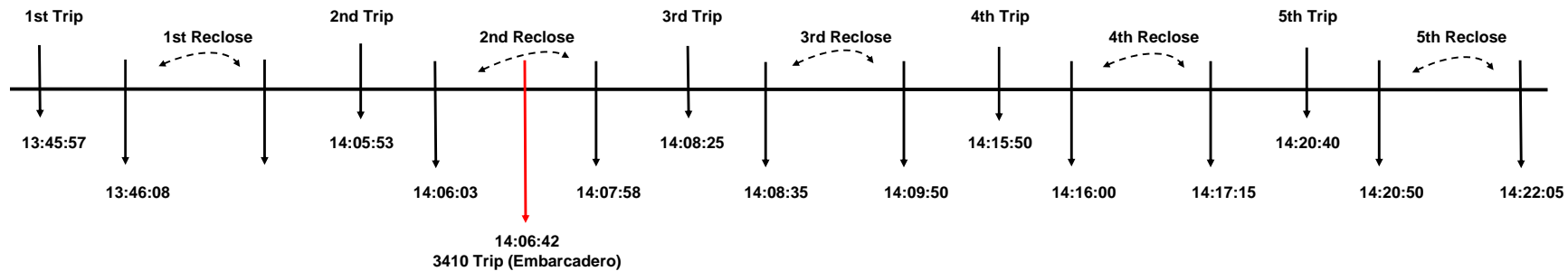
A procedure for implementing these changes is being developed and all modified installations will be brought into compliance with this procedure.

### **Conclusion**

The status and conclusion from the current July 24 Martin investigations are summarized as:

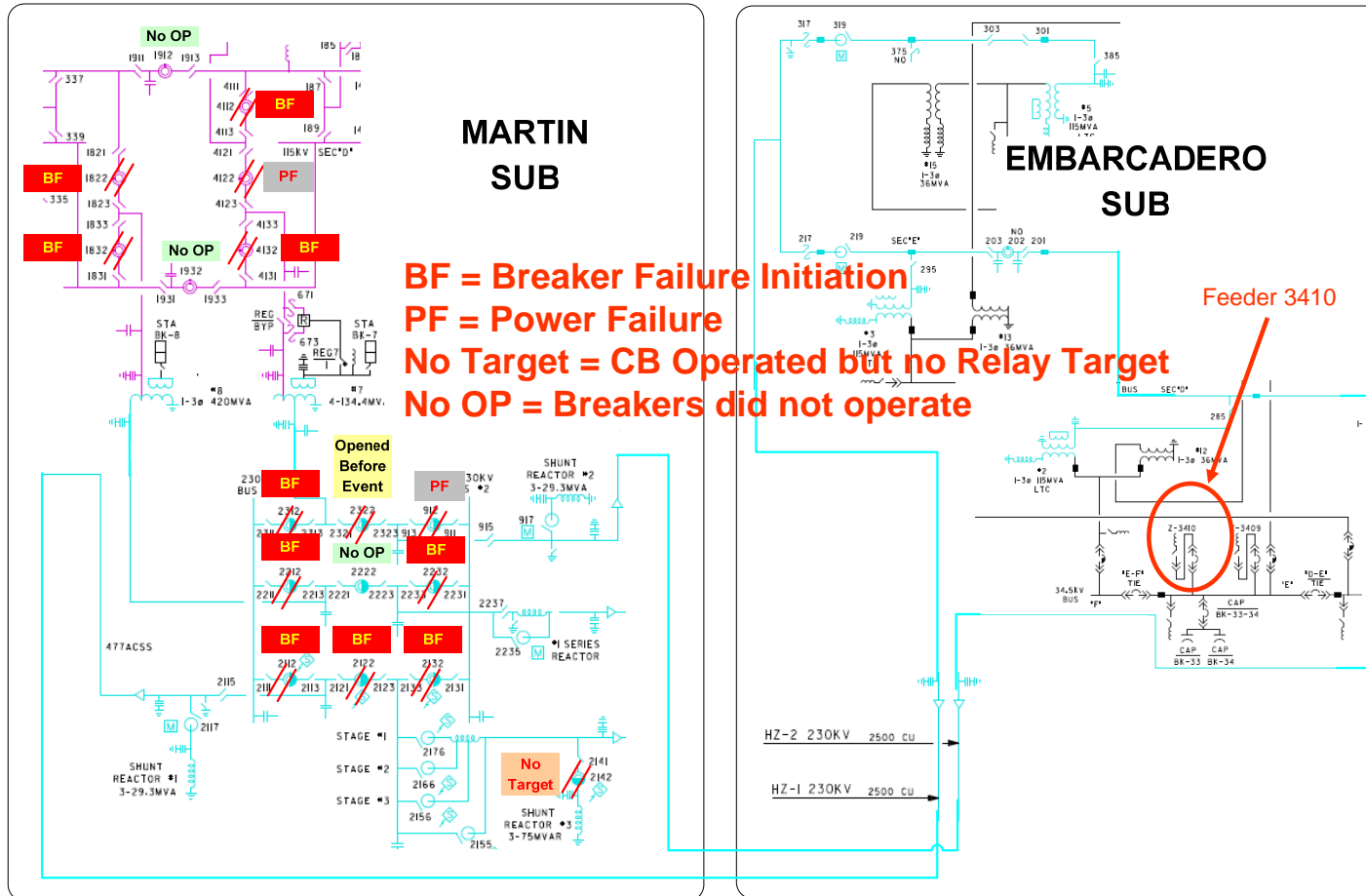
1. The combined cause of the false tripping of twelve breaker failure relays on July 24, 2007 at the Martin substation was the incorrect wiring of a tester that was being used to test a spare breaker and the internal components of these specific newer model breaker failure relays involved. The wiring error subjected the breaker failure relays to a 60Hz signal and exposed their susceptibility to this false signal.
2. Testing of the breaker failure relays revealed that:
  - a. Only newer units of the breaker failure relays respond in this manner – older units are not susceptible to the 60Hz AC voltage that resulted from the incorrect tester wiring and caused them to false trip.
  - b. Older breaker failure relays are not susceptible to DC power supply transients that were also found to cause the newer units to false trip.
  - c. The newer units can be modified to achieve immunity to both the AC and DC transients such that they perform in a manner comparable to the older models. The modification involves the addition of a resistor to drop the input impedance, and an increase in its contact recognition time from 8 milliseconds to 12 milliseconds.

3. The extent of the relay susceptibility issue has been bounded since only newer model breaker failure relays are susceptible to the 60Hz AC stress that was imposed on the relays during the July 24 events. There are approximately 140 breaker failure relays that have been delivered to PG&E that require modification.
4. The overall system risk has been greatly reduced by identifying a susceptibility in the breaker failure relay and identifying modifications that make it more immune to the identified disturbances.
5. On-going actions include:
  - Implementing further breaker failure relay modifications to mitigate recurrence.
  - Review test procedures to reduce the probability of technician error.
  - Perform a field test of the battery charger in the 230kV control room to learn more about the voltage excursions seen on the battery voltages. While this testing does not address the cause of the July 24 event, it may be relevant in the March and April false trip events.



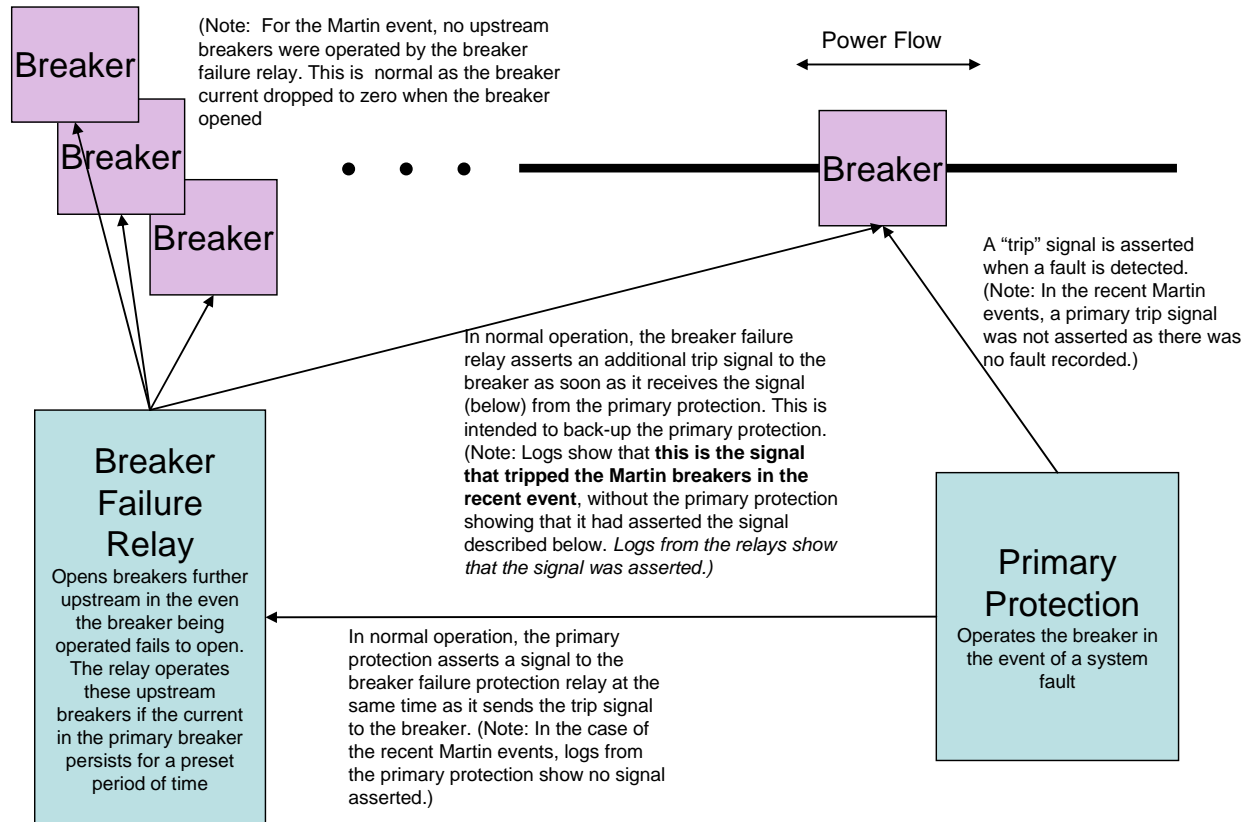
**FIGURE 1: Event Timeline**

## Martin Operation: Breakers Tripped



**FIGURE 2: Breaker Status During July 24 Event**

# Breaker Failure Relay Functionality



**FIGURE 3: Protection Scheme**

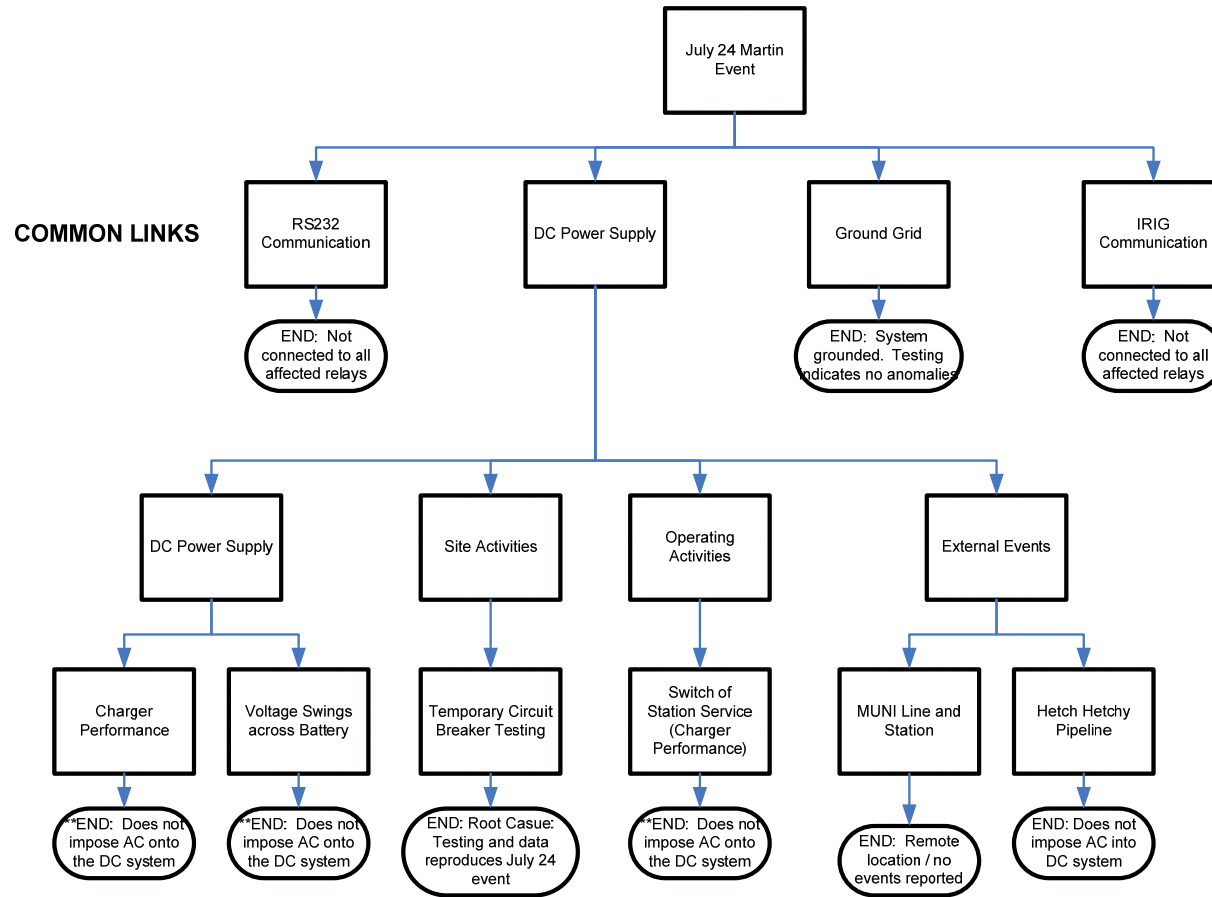
Test Stimuli	Original Relay (new)		Original Relay (old)	Replacement Relay <sup>1</sup>
	Unmodified	With 47kOhm Resistor		
DC Pulse	Breaker False Tripping and Retrip	No False Trip	No False Trip	No False Trip
AC Input	Breaker False Tripping and Retrip	Some False Tripping at About 120V ac	Direct Application of 120V Caused No False Trip	AC Input Over 76V Caused False Trip
AC Input with increase in contact recognition time extended to 12 milliseconds		No False Trip	No False Trip	

Notes:

- 1) Relay set to retrip with ½-cycle delay
- 2) Red shading indicates relay did not pass test. Green shading indicates relay passed test. Yellow shading indicates relay did not completely pass test.

**FIGURE 4: Breaker Failure Relay False Trip Test Results**

# DRAFT



**\*\* On-going investigation relative to the March and April events. However, these are not a cause of the July 24 event.**

**FIGURE 5: Potential Initiating Causes**