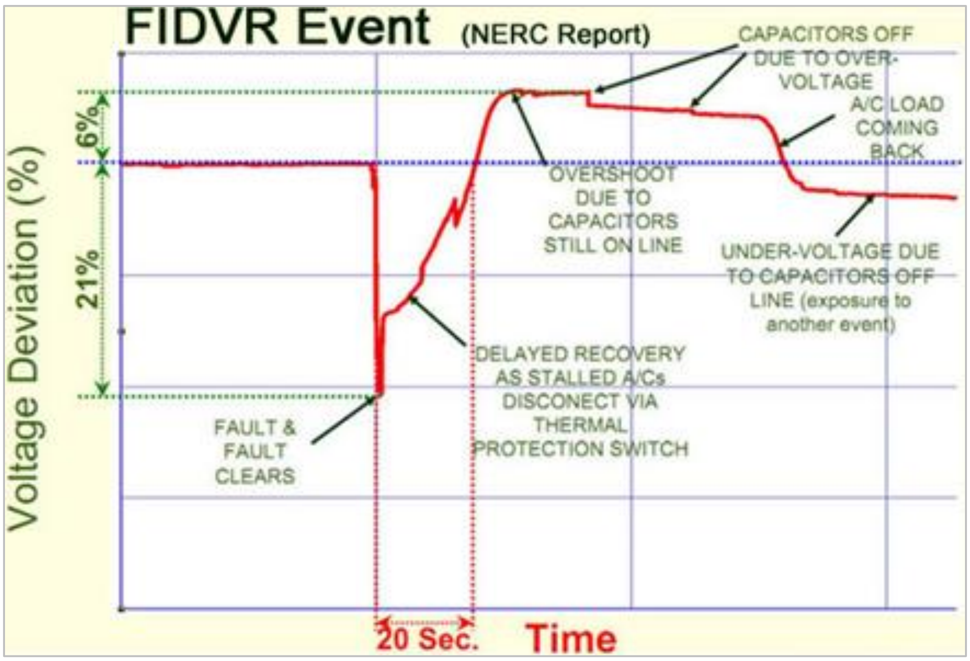
2014 FIDVR Events Analysis on Valley Distribution Circuits



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Southern California Edison (SCE), an Edison International company, is one of the nation's largest investor-owned utilities, serving more than 14 million people in a 50,000-square-mile service area within Central, Coastal and Southern California. The utility has been providing electric service in the region for more than 125 years.

SCE's service territory includes about 430 cities and communities with a total customer base of 4.9 million residential and business accounts. SCE is regulated by the California Public Utilities Commission and the Federal Energy Regulatory Commission.

In 2012, SCE generated about 25 percent of the electricity it provided to customers, with the remaining 75 percent purchased from independent power producers. One of the nation's leading purchasers of renewable energy, SCE delivered nearly 15 billion kilowatt-hours of renewable energy to its customers in 2012, enough to power 2.3 million homes.

Advanced Technology is the organization in SCE's Transmission and Distribution business unit and the Engineering & Technical Services (E&TS) organization that investigates advanced technologies and methodologies to support the utility's goals to provide safe, reliable and affordable energy while overcoming the challenges associated with the generation, transmission and distribution of electricity such as: the integration of variable energy resources, cascading outages and the effects of customer loads.

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This report was created as a result of work sponsored by the U.S. Department of Energy through the Lawrence Berkeley National Laboratory and SCE's Research Development and Demonstration Balancing Account, which was initially established in 1988 as part of customer rates and performed by its Advanced Technology organization. This report has not been approved or disapproved by SCE nor has SCE verified the accuracy, adequacy, and safety of the information in this report.

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SCE follows OSHA and internal safety procedures to protect its personnel and encourages its partners and contractors to these safety practices as well.

The author acknowledges the efforts of SCE Senior Engineer, Richard Bravo who was the SCE lead for this project in previous years and contributed to the conclusions made in these multiyear reports. Additionally the author acknowledges SCE intern Manuel Garcia who supported with the collection and analyses of the data.

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1.0 INTRODUCTION

The majority of fault-induced delayed voltage recovery (FIDVR) events on the SCE system occur during summer monsoonal season. These weather conditions bring rain and thunderstorms to hot climate areas where high concentrations of residential air conditioners (RAC) are in use. During these conditions, lightning strikes to the distribution and sub-transmission systems may result in system faults. If these faults decay the voltage below a certain threshold, they can cause air conditioner motors to stall. As a result, the RAC stalling behavior prevents voltage from immediately recovering, provoking FIDVR events.

FIDVR events have been typically recorded in the transmission system as in Figure 1.0.1 which shows the voltage being depressed to 79 percent during a system fault. The voltage is kept suppressed by the stalling of RAC and slowly recovers as the RAC's thermal overloads start opening, disconnecting the RAC from the system. The voltage does not stop at pre-fault voltage, but instead it keeps increasing. This incremental change is due to the high amount of customer load disconnecting from the system and system capacitors remaining online. The system voltage starts decreasing to pre-fault levels when the system capacitors disconnect due to the over-voltage and customer load starts coming back to the system.

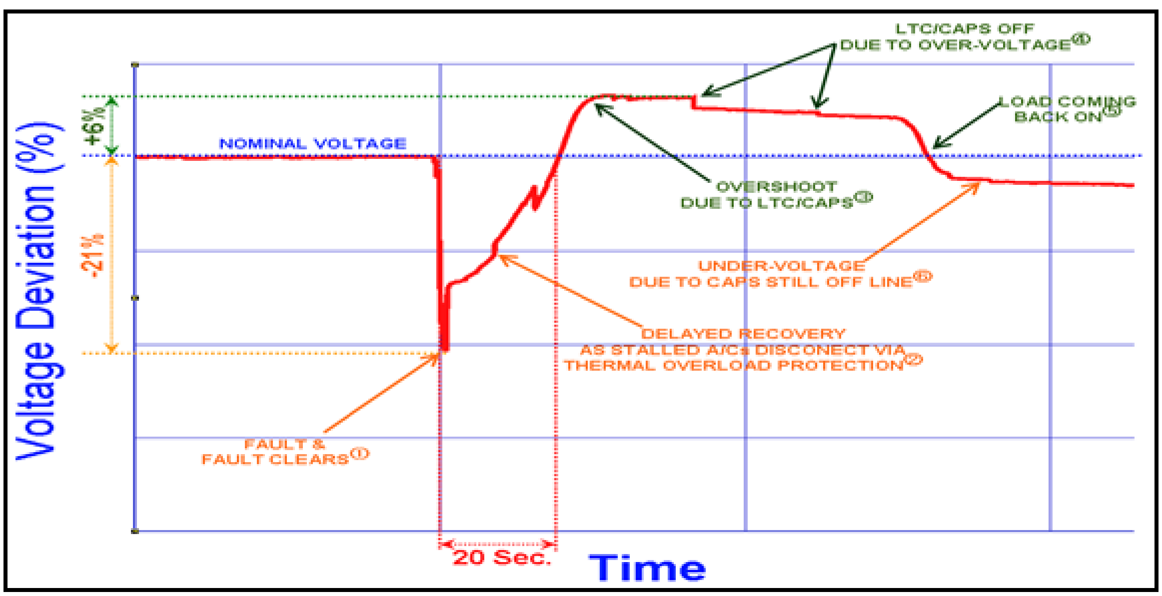

Figure 1.0.1 FIDVR Anatomy

In most cases, these events are localized and do not cascade or spread throughout the transmission system to cause outages. There is concern that if these faults occur in the transmission system, it would cause all air conditioners in that region to stall. This could have detrimental impacts to the grid, leading to issues such as blackouts or power plants tripping.

The Western Electricity Coordinating Council (WECC) has been instrumental in the investigation of FIDVR events. Additionally, its members had tested 27 RAC units during various voltage and frequency deviations and determined that:

- RAC units typically stall within 3 cycles
- Stalling voltage varies with the outdoor temperature
  - 60% voltage at 80°F
  - 65% voltage at 100°F
  - 70% voltage at 115°F
- Thermal overload protection switches (TOPS) typically open to disconnect the RAC units within 2 to 24 seconds depending on the stalling current (the lower the current is the longer it takes to open)
- Power contactors disconnect the RAC when voltage drops approximately below 53%, but contactors will reclose with voltage recovery because the thermostat contact is maintained closed
- Scroll RAC tend to restart sooner after they stalled once voltage recovers
- Some scroll compressors tend to run backwards instead of stalling

Although this information has been critical for developing an accurate air conditioner model, detailed field data is an important tool needed to fine tune these FIDVR event characteristics in the aggregate or composite load models used for system impact studies. This more detailed data can also be used to validate distribution circuit models.

The Valley system delivers approximately 1,500 MW during summer peaks serving approximately 300,000 residential and 30,000 commercial/industrial customers. Figure 1.0.2 below shows loading conditions in the Valley region for previous years. Based on the difference in summer loading conditions, it is estimated that 60% of load at Valley during the summer is attributed to air conditioners. Similarly these maximum peak loading values have remained similar during the past three summer seasons, shown in Figure 1.0.3, when SCE began capturing the voltage and current data detailed in this report.

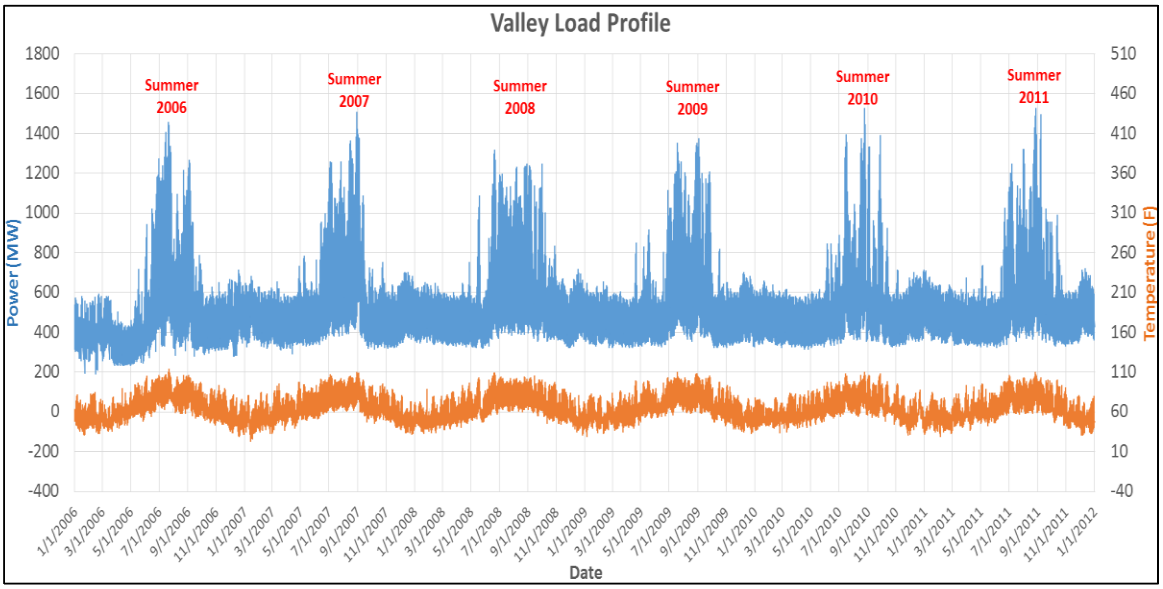

Figure 1.0.2 Valley Load Profile (2006 - 2011)

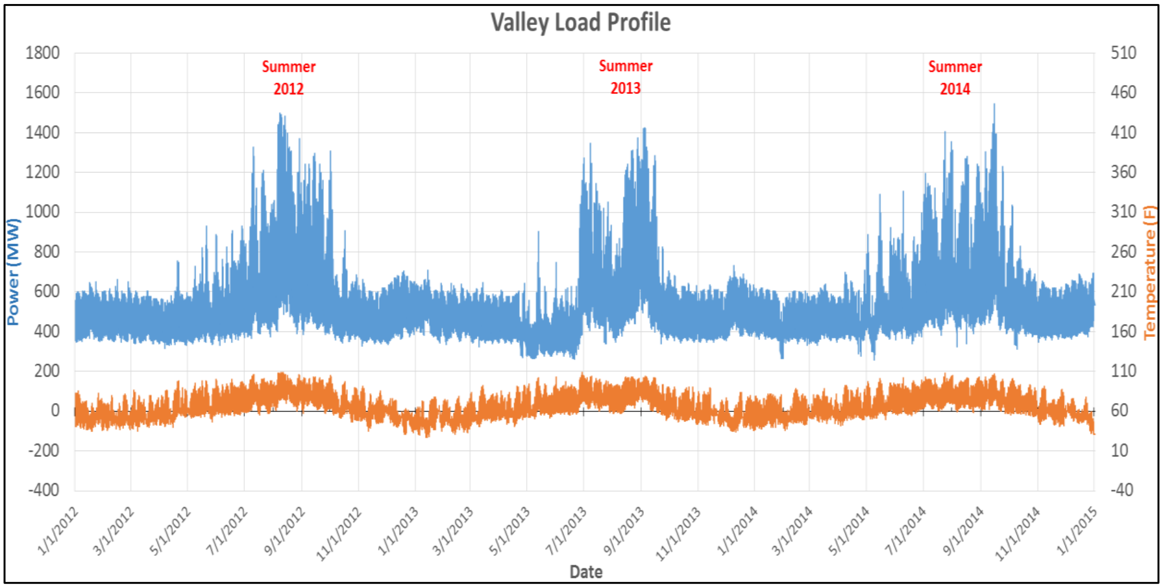

Figure 1.0.3 Valley Load Profile (2012 - 2014)

2.0 OBJECTIVE

In an effort to examine the detailed characteristics of FIDVR events in distribution circuits, Southern California Edison (SCE) installed 22 power quality (PQ) recording devices on 18 of its Valley Substation's 24 sub-transmission circuits that serve the utility's residential and commercial customers. Additionally, one PQ device was installed in a 12 kV distribution circuit that feeds directly from the 115 kV Valley's substation and two PQ devices on a circuit with solar PV generation.

There are a variety of reasons for recording this type of data, most importantly the need to:

- Understand how FIDVR events evolve and impact local residential and commercial customers
- Build, validate and/or tune computer models used for FIDVR system impact studies
- Validate circuit models
- Verify other load conditions during these events

This SCE multiyear study (2011 to 2014) is part of an integrated program of FIDVR research sponsored by the U.S. Department of Energy through the Lawrence Berkeley National Laboratory. It is intended to promote national awareness, improve understanding of potential grid impacts, and identify appropriate steps to ensure the reliability of the power system.

3.0 POWER QUALITY RECORDER SETUP

Advanced Technology's DER laboratory put together a flexible power quality (PQ) recording device to be installed in the field, specifically at distribution transformers, as shown in Figure 3.0.1. The PQ recording devices in this setup can record up to five voltages and five currents during steady-state conditions as well as during system events.

These devices were programmed to record the following when an event is triggered:

- Root mean square (RMS) data captured at 1 sample/cycle (for approximately 17 seconds)
- Sinusoidal waveforms captured at 128 samples/cycle (for approximately 16 cycles)

To ensure the recording of FIDVR events and avoid numerous minor events, the PQ device's voltage trigger parameters were set up as follows for both line-to-line and line-to-neutral measured voltages:

- Under-voltage triggering threshold at 80% of nominal
- Over-voltage triggering threshold at 110% of nominal

In addition to the capturing event data, the PQ devices were set to record trend or steady state data in 5 minute and 1 minute intervals. The 5 minute data is captured onto weekly trend files while the 1 minute data is stored in daily trend files. This data may later be used to assess the daily load performance.

The data is recorded onto a secure digital (SD) memory card for easy access and removal from the PQ device. The recorded data is captured and translated into comma separated values (csv) file format.

Every device was equipped with an uninterruptible power supply (UPS) to provide power for up to nine minutes so that it will record during events of low voltage without compromising the data. A one ampere circuit breaker was added for electrical protection. Each of the PQ devices and corresponding modules were placed in a small enclosure allowing it to be placed in the field.

Each SCE PQ recorder setup has the following components:

- PQube module: records data and provides the voltage inputs
- Current module: provides current inputs and Ethernet connection for communications
- Power supply: transforms the input voltage down to 24 VAC to power the PQube
- Circuit breaker: electrically protects the PQ recorder
- Current transformers (CTs) with cannon plug connector: transforms the currents to 0.333V at full scale. The cannon plug connector provides flexibility for field installation
- Voltage leads with banana plug connectors: provides flexibility for voltage measurements in a field installation
- Din rail with end clamps: secures modules, power supplies, and circuit breakers in place
- Enclosure: protects the PQ recorder from environmental conditions

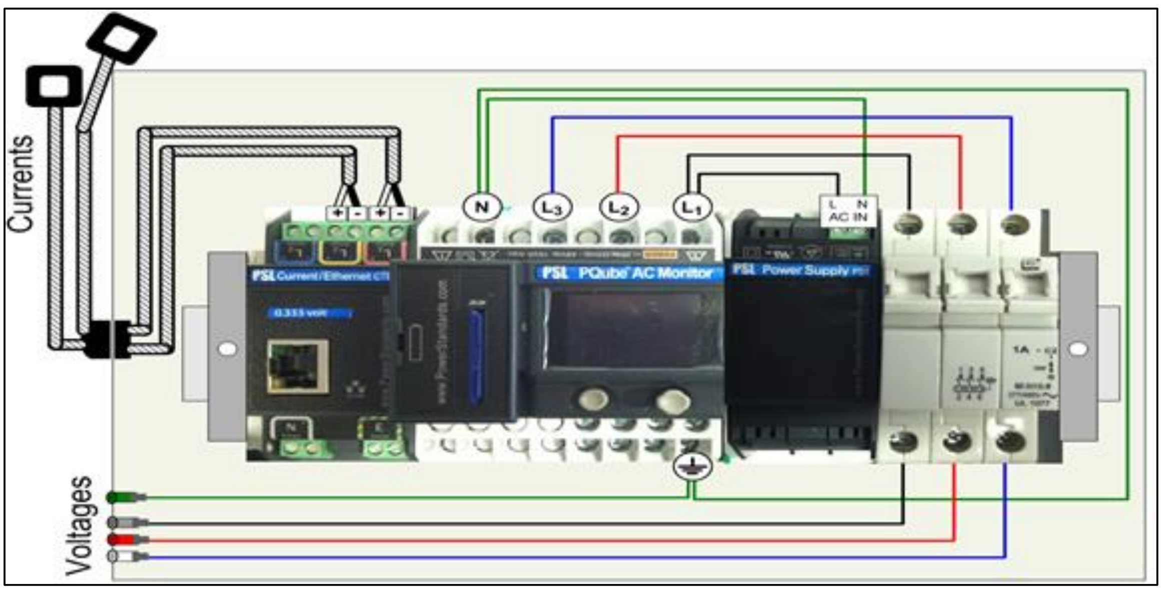

Figure 3.0.1 SCE PQ Recorders Setup

4.0 FIELD INSTALLATION

At the beginning of the study, the PQ recorders were installed on distribution capacitor controllers capturing split-phase 240 V line-to-line voltage. While several voltage events were recorded, this installation did not provide a means of measuring current; therefore, no real or reactive power profiles were attained from this data.

In 2012, the PQ recorders were upgraded with current transformers (CTs) to capture current data as well. These devices were installed in distribution pad mount transformers serving primarily residential customers. The installation setup diagram shown in Figure 4.0.1, illustrates the transformer's primary side 6.9 kV phase-to-ground and secondary side 240 V line-to-line connections.

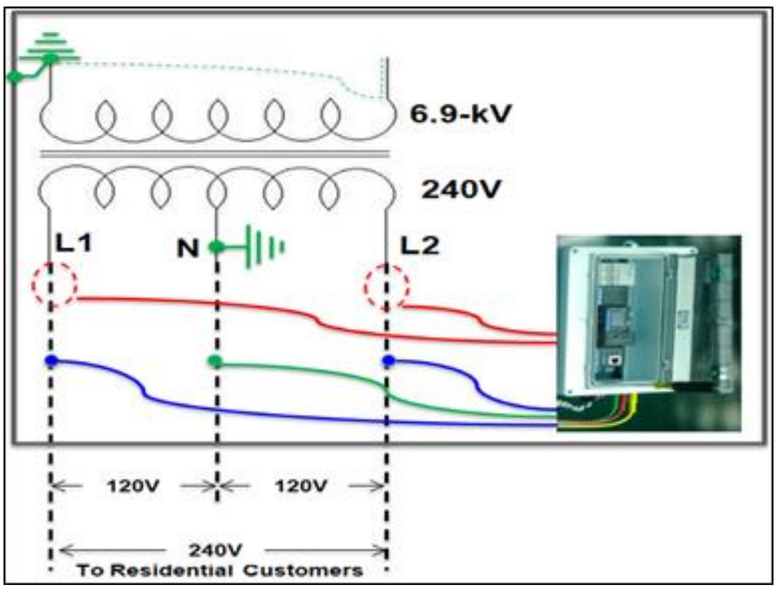

Figure 4.0.1 PQ Recorder Pad Mount Transformer Installation Diagram

One of the actual residential padmount transformer installations is shown in Figure 4.0.2. The primary side (6.9 kV) has two boot connections where one goes into one pad-mount transformer and the other leaves, going to a different pad-mount transformer.

The concentric wires from both cables are bolted together and connected to the transformer's chassis and neutral of the secondary side. The concentric has two main purposes:

- Provide a path for ground currents
- Serve as a ground to the pad mount transformer and the customers

The secondary side of the transformer has three terminal blocks with three cables (L1, L2, and neutral rated at 240 V line-to-line) going to customer main panels. These terminal blocks contain the CTs and voltage leads for the installed PQ device. The neutral is connected to ground at this point.

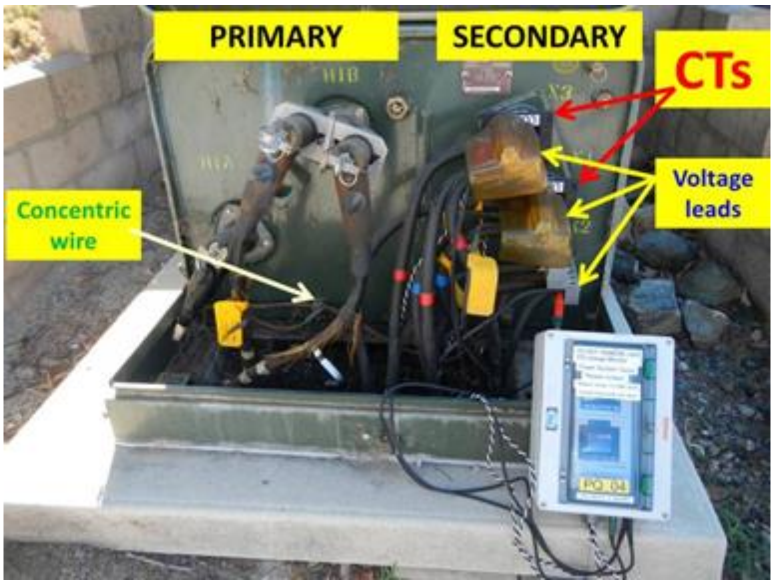

Figure 4.0.2 PQ Recorder Field Installation in a Pad Mount Transformer

A total of 25 PQ recorders were in service in 2013. In addition to the 22 PQ recorders installed in 2012 a 23rd installation was added to residential transformer in another 115kV circuit in the Valley system. Also, two PQ recorders were installed on the secondary side of the three-phase transformers serving commercial loads. The secondary side of the transformer consists of measurements at Phase A, Phase B, Phase C and neutral at 120V/208V.

Eleven of these PQ recorders were removed in 2014 and replaced with newer devices and enclosure assemblies. To avoid confusion regarding the device identification numbers, the data from the newer devices was cataloged under the previous identification numbers from the same installation site.

Table 4.0.1 provides the details for each of the PQ installation sites, including the two installed on a distribution circuit with an 8MW solar PV rooftop plant and commercial load. All of the single-phase (240 V) padmount transformers were only serving residential customers.

PQube		Location on Circuit (Middle of Line or End of Line)	# of Customers on Padmount Transformer
#	Voltage (L-L)		
1	240VAC	End	13
2		Middle	15
3		End	8
4		Middle	17
5		Middle	16
6		Middle	6
7		End	8
8		Middle	7
9		Middle	14
10		Middle	20
11		Middle	--
12		End	6
13		Middle	8
14		Middle	16
15		End	15
16		Middle	8
17		End	13
18		End	8
19		Middle	19
20		End	--
21		End	10
22		Middle	10
46		Middle	14
Solar PV			
49	208VAC	3Φ Transformer outside 8 MW Solar PV	11
50	208VAC	3Φ Transformer further away 8 MW Solar PV	--

Table 4.0.1 Valley PQ Locations Information

5.0 DISTRIBUTION CIRCUIT LOCATIONS

In recent years, SCE has been analyzing available phasor measurement unit (PMU) data (collected as far back as 2002) to document air conditioner stalling events that have previously occurred on its system. According to this data, at the transmission and sub-transmission levels, the Valley system appears to be one of the networks more susceptible to FIDVR events; therefore, the study team placed PQ devices on various distribution circuits throughout the Valley substation region.

The Valley network has the following characteristics:

- Two 500 kV lines come from Devers and one from Serrano
- Transmission system contains two 115 kV busses, Section A&B (Western side) and Section C&D (Eastern side)
- Each of the 115 kV substation buses feeds a meshed sub-transmission system.
- 24 meshed sub-transmission 115 kV substations
- Sub-transmission 115 kV substations with two types of distribution circuits 33 kV and 12 kV, most of which are 12 kV
- 12 kV circuits used for both commercial and residential circuits with pad-mount and pole-mount transformers to serve customers. The 12 kV residential pad-mount transformers step the voltage down from 6.9 kV to 240 V line-to-line and typically serve several customers
- The 33 kV circuits are used for longer distribution circuits (mainly rural) instead of the 12 kV distribution circuits
- All PQ devices were installed in the pad-mount transformer's secondary (either 240 V or 208 V line-to-line) side that will feed to customers

The PQ monitors were installed in pad-mount transformers within 18 of Valley's 24 meshed sub-transmission (115 kV) systems as shown in Figure 5.0.1. One device (PQ15) was installed in a 12 kV distribution circuit connected directly into Valley substation. The device installations were located either at the middle or the end of the line for each distribution circuit. These data recording devices were also placed on different phases of the circuits to acquire a diverse collection of event data.

Two PQ devices were also installed to monitor all three phases on a 12 kV circuit with commercial solar PV generation. The 12 kV circuit is located in one of the meshed sub-transmission systems in the Valley area. One of these devices (PQ49) was placed at the load serving transformer nearest to the solar PV installation. The other PQ device (PQ50) was placed towards the end of line, further away from the solar PV generation and circuit substation.

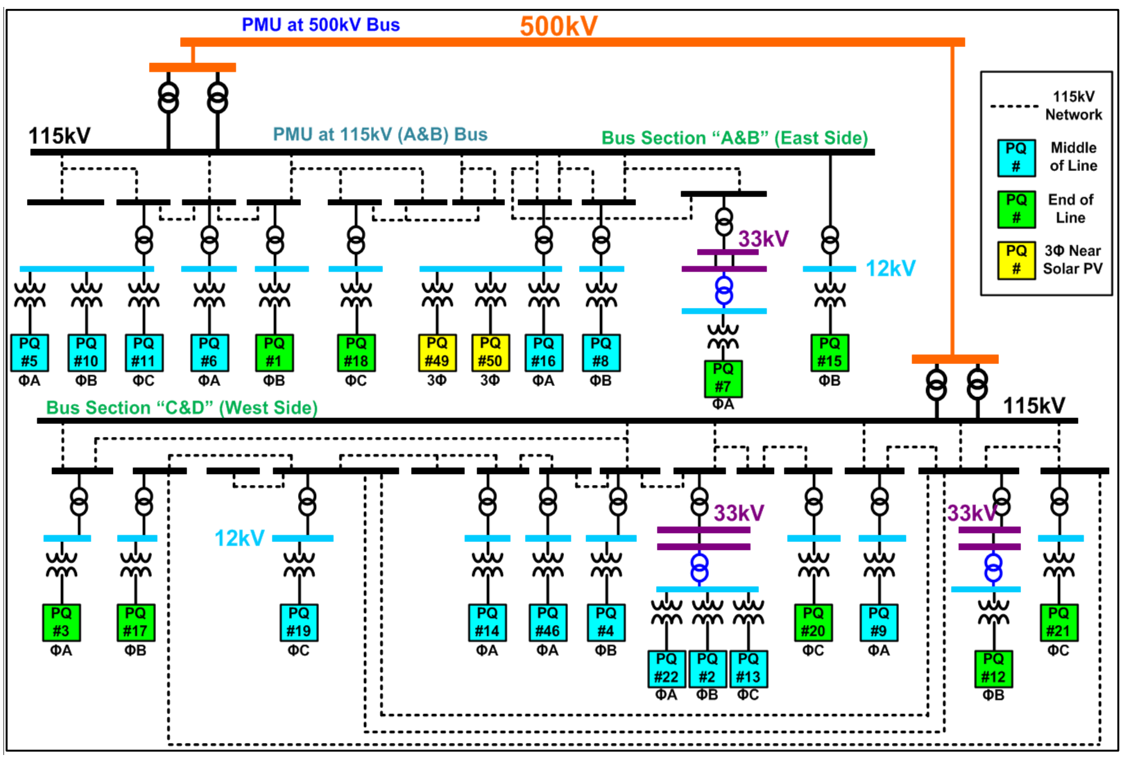

Figure 5.0.1 Valley PQ Locations Diagram

6.0 SUMMER 2014 DISTRIBUTION FIDVR EVENT ANALYSIS

The events analyzed for this study were recorded throughout the summer season in the year 2014. These devices were installed at the customer padmount transformers, also referred to as the point of common coupling (PCC), in May and removed in November. While a variety of the events were captured, these particular events were classified as distribution level FIDVR events.

All voltage values (%) shown in the corresponding figures have been measured at the secondary side of the transformer with a base of 240 V line-to-line with the exception of PQ devices 49 and 50 that were installed at 3-phase transformers with a base of 120 V_{L-N} for each phase.

Please note that PMU devices were not functioning and unable to capture data at the Valley 500 kV and 115 kV buses during events that occurred after early August 2014.

6.1 FIDVR Event #1 (July 7, 19:57 PDT)

The RMS data for Event #1 shown in Figure 6.1.1 was captured from PQ 18 located on phase C on the Valley 115kV section A&B bus. No information was documented by the Grid Control Center (GCC) for this location at the specified time.

- The event resulted in a small voltage deviation (3% of nominal) on the sub-transmission systems as evidenced by the PMU data in the Valley region
- Only capturing data at a single PQ device seems to indicate that this was a localized FIDVR event on the distribution system
- Voltage at the PCC initially drops to 62% and goes as low as 56% of nominal where load stalling begins to occur
- Real power (P) and reactive power (Q) increased significantly
  - P = 2.6X at V = 88% within 1 second after the fault
  - Q = 5.9X at V = 88% within 1 second after the fault

- The event lasted approximately 6 seconds until distribution voltage finished recovering to its pre-event condition
- Most of the loads begin disconnecting 5 seconds after the fault occurs due to RAC's thermal protection
- Approximately 60% of the load was ultimately lost 12 seconds after the event began
- A portion of customer load restarted shortly after the 16 second mark on the provided figure below

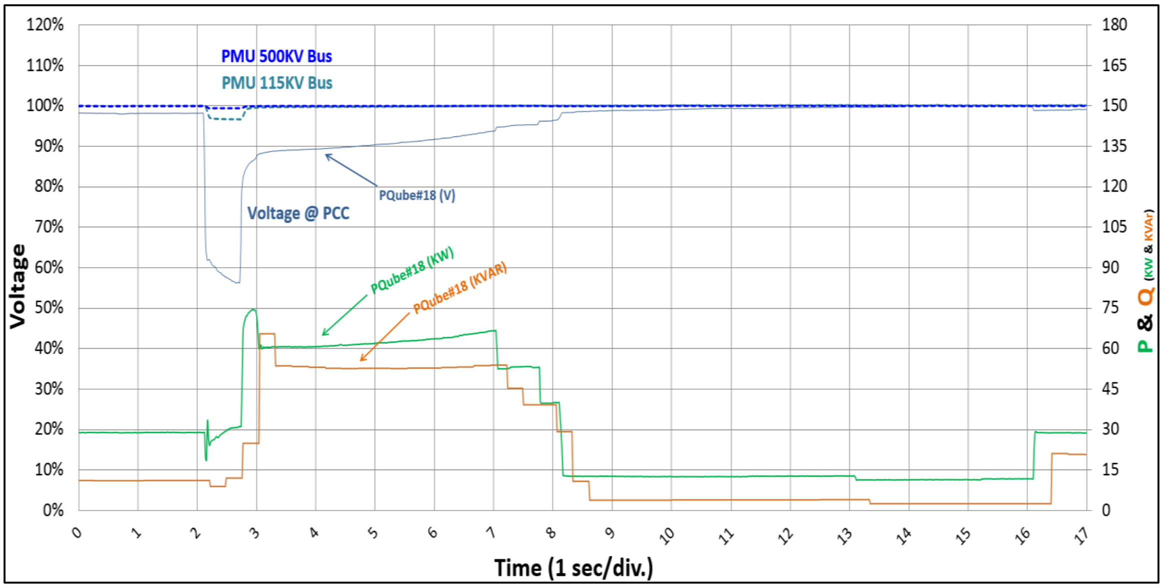

Figure 6.1.1 FIDVR Event #1 (July 7, 19:57 PDT) RMS Data [PQ 18]

The sinusoidal waveform data from the PQ 18 device, shown in Figure 6.1.2, indicates that the fault occurred at the 80 degree angle mark of the Line 1 voltage waveform. Although peak current increases slightly, it does not appear that the sinusoidal data captures fully stalled loads. The RMS data indicates that this sudden increase in real and reactive load occurs outside the window of the recorded sinusoidal waveform data.

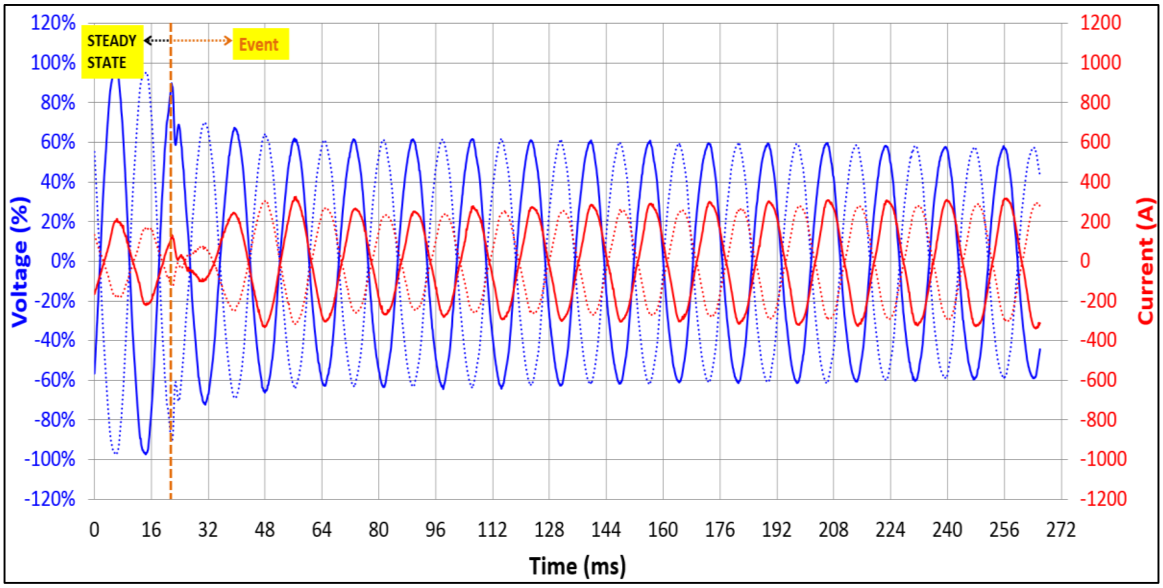

Figure 6.1.2 FIDVR Event #1 (July 7, 19:57 PDT) Sinusoidal Data [PQ 18]

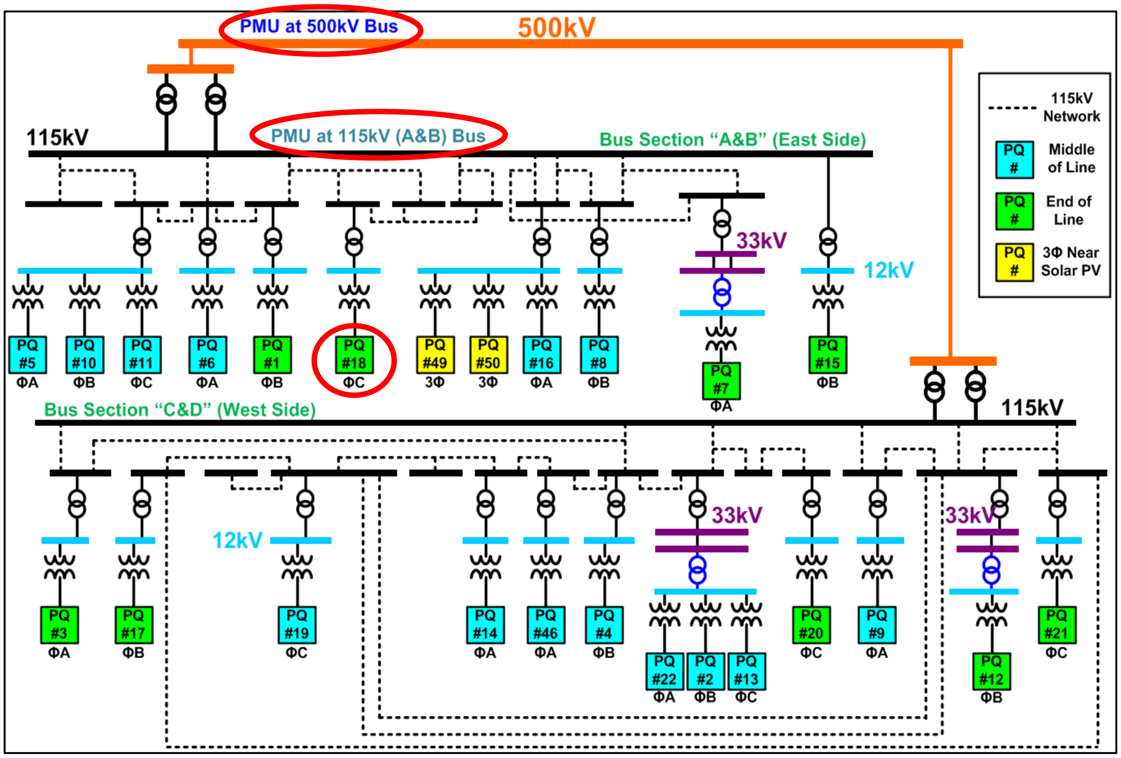

Figure 6.1.3 FIDVR Event #1 (July 7, 19:57 PDT) Monitoring Locations

6.2 FIDVR Event #2 (September 12, 12:55 PDT)

The Grid Control Center (GCC) reported a fire of undetermined origin burning under and past a 500 kV line on the system. At 12:55, a fault was indicated and the 500 kV line relayed as a result. The RMS data for Event #2 shown in Figure 6.2.1 exhibits these characteristics:

- The event spread through the distribution system as evidenced by the multiple PQ device recordings at different monitoring locations
- During the fault captured, the voltages at the PCC drop to as low as 51% of nominal where RACs appear to stall at one of PQ devices
- Real power (P) and reactive power (Q) at PQ 15 increased as such
    - P = 1.6X at V = 88% within 1 second after the fault
    - Q = 3.7X at V = 88% within 1 second after the fault
- The various circuits took approximately 4.5 seconds respectively for voltage to recover to their pre-event conditions
- Stalled loads begin disconnecting a couple seconds after the fault
- Approximately 29% of the load was lost due to RAC's thermal protection by the 7 second mark shown on Figure 6.2.2
- The loss of load provoked a maximum over-voltage of 5% above nominal on the assorted distribution circuits

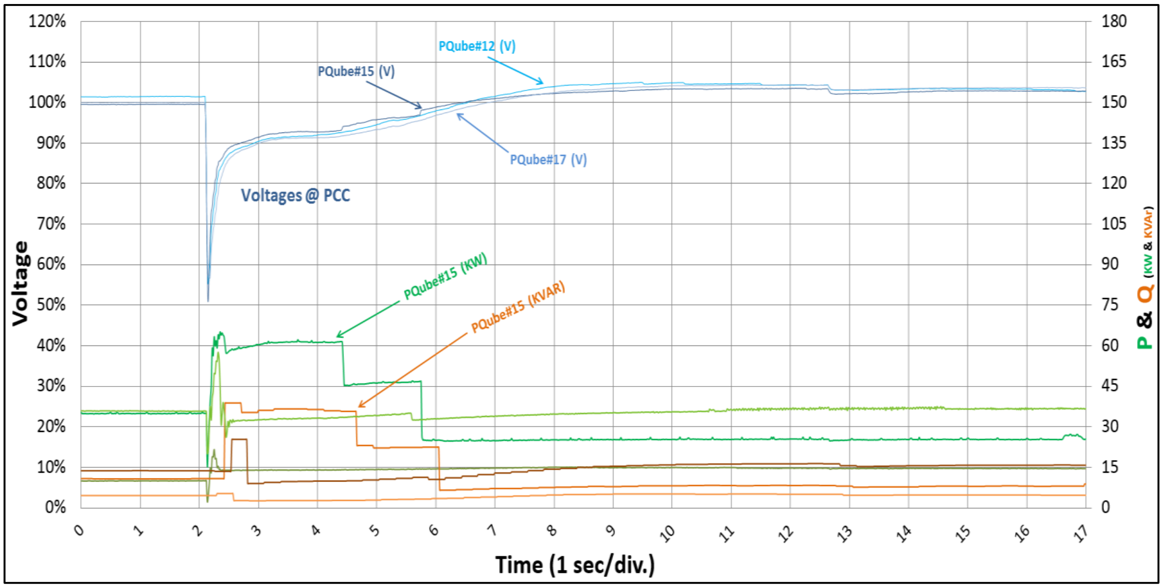

Figure 6.2.1 FIDVR Event #2 (September 12, 12:55 PDT) RMS Data [PQ 12, 15, and 17]

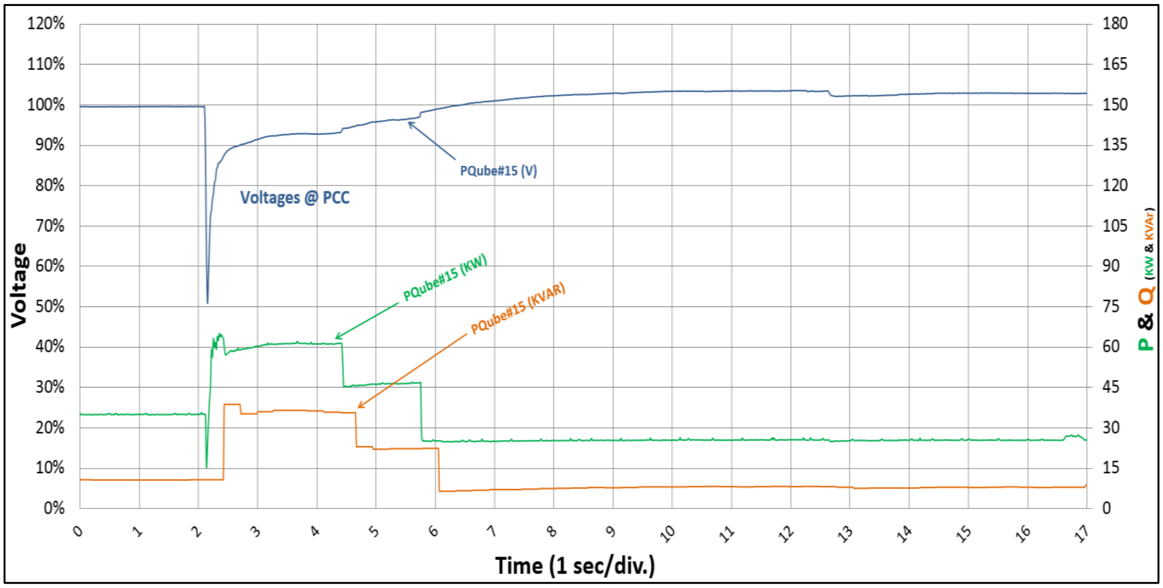

Figure 6.2.2 FIDVR Event #2 (September 12, 12:55 PDT) RMS Data [PQ 15]

The sinusoidal waveform data from the PQ 15 device, shown in Figure 6.2.3, indicates that the fault occurred at the 40 degree angle of the Line 1 voltage waveform. Stalling appears to occur in approximately 3 cycles after the event begins as indicated by the peak current dramatically increasing and the power factor changing. The current is nearly 220 amps-peak before the event and as high as 620 amps-peak during the event.

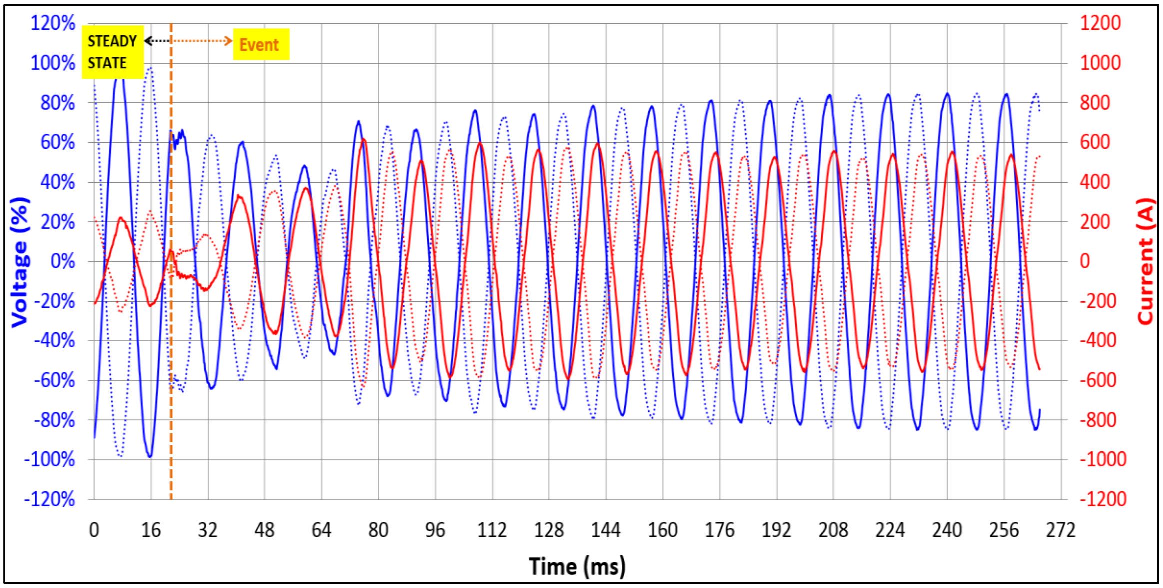

Figure 6.2.3 FIDVR Event #2 (September 12, 12:55 PDT) Sinusoidal Data [PQ 15]

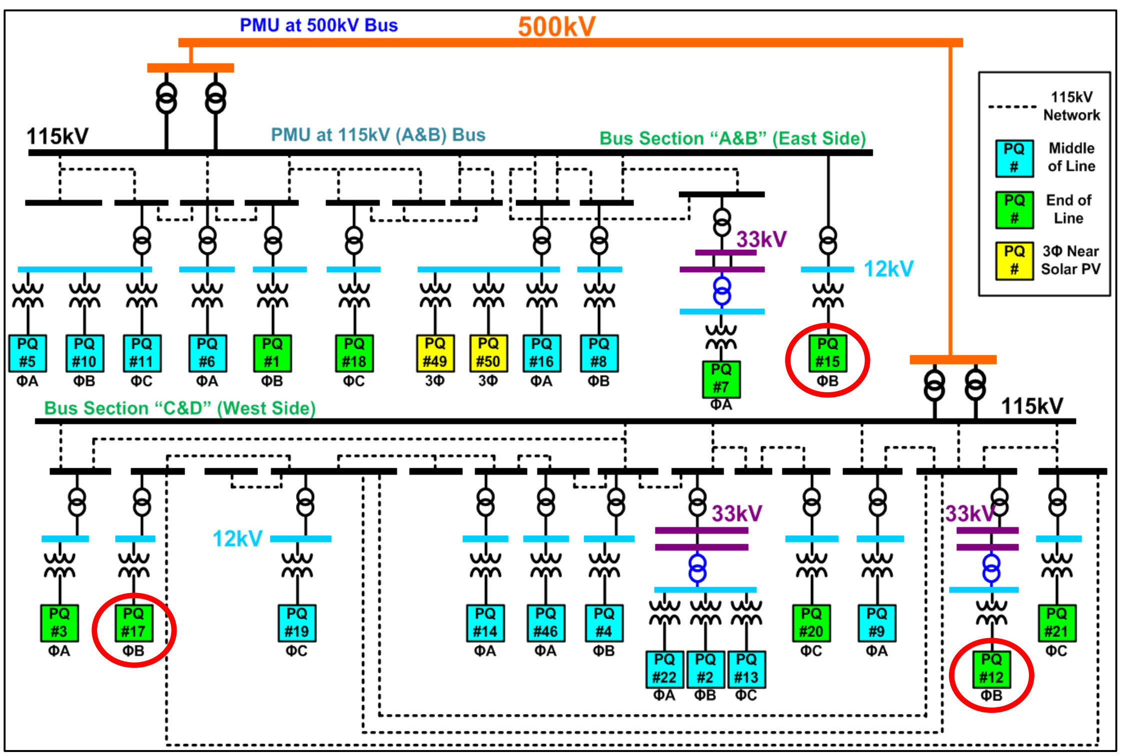

Figure 6.2.4 FIDVR Event #2 (September 12, 12:55 PDT) Monitoring Locations

7.0 ADDITIONAL VOLTAGE EVENTS

The following voltage events were also captured along with confirmed FIDVR events during the summer of 2014. The characteristics observed during these events may imply some degree of voltage recovery and/or stalling but cannot be characterized as FIDVR events. Some of these events do not have significant delayed voltage recoveries at the distribution level (most of the faults return to 95% nominal voltage in less than 1 second). Other events do have significant delayed voltage recoveries and may very well be FIDVR events but cannot be classified as FIDVR because there is no evidence of stalled loads (based on real and reactive power profiles) from the data captured.

All voltage values (%) have been measured at the secondary side of the transformer with a base of 240 V line-to-line with the exception of PQ devices 49 and 50 that were installed at 3-phase transformers with a base of 120 V line-to-neutral for each phase. This monitoring location on the customer transformer will also be referred to as the PCC.

Again, please note that not all plots shown have PMU data from Valley 500 kV and 115 kV buses since these monitoring devices were down sometime after early August.

7.1 Event #1 (May 16, 23:34 PDT)

The RMS data for the following event shown in Figure 7.1.1 was captured from PQ 16 located on phase A on the Valley 115kV section A&B bus. No information was documented by the GCC for this location at the specified time.

- **No significant delayed voltage recovery** or over-voltage was recorded
- The event caused a minor voltage deviation on the sub-transmission systems as evidenced by the PMU data in the Valley region. Nevertheless only a single PQ device captured an under-voltage profile on the distribution system.
- The voltage at the PCC decreased to 70% during the initial fault. As voltage began to recover, another fault occurred dropping the secondary voltage to as low as 50%.
- PMU data shows the sub-transmission voltage decreasing slightly to 95% of nominal

- Real power (P) and reactive power (Q) as such
  - P = 2.9X at V = 55% within 1 second of the fault (as voltage is about to recover)
  - Q = 2.8X at V = 55% within 1 second of the fault (as voltage is about to recover)
- Distribution voltage completely recovers to pre-event voltage in approximately 3.15 seconds. However, this voltage is nearly completely recovered (97% of nominal) within the 1st second of the event.
- Loads begin disconnecting and/or restarting approximately 3 seconds after the initial under-voltage event occurs
- Approximately 8% of load was lost (based on pre-event load) immediately following the voltage recovery, and an additional 10% of load was lost several seconds later
- Air conditioner load was likely low during the time of this particular event

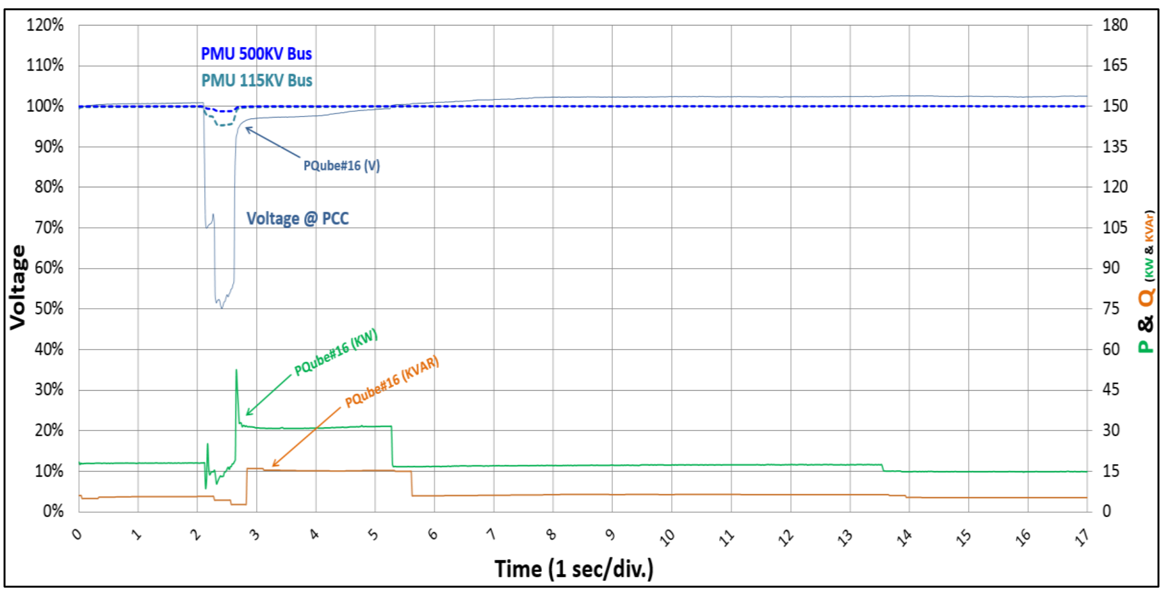

Figure 7.1.1 Event #1 (May 16, 23:34 PDT) RMS Data [PQ 16]

The sinusoidal waveform data from the PQ 16 device indicates that the first fault occurred at the 50 degree angle of the Line 1 voltage waveform and the second fault at the 100 degree angle of Line 1 voltage. Peak current increases slightly for a brief time, but no significant increase in current is captured. The RMS data indicates that the increase in real and reactive load occurs outside the window of the recorded sinusoidal data.

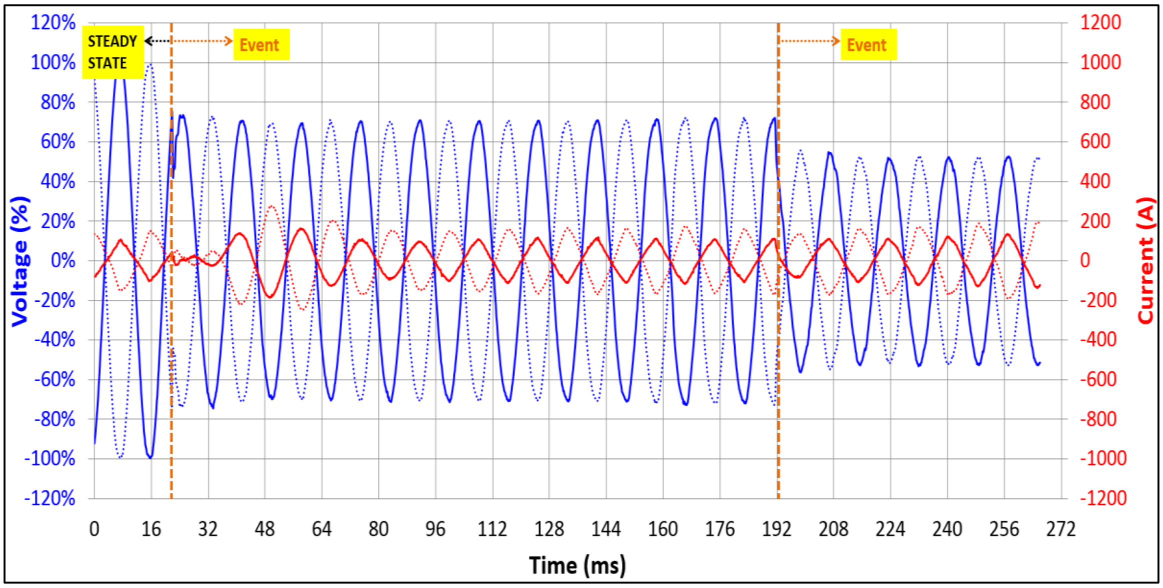

Figure 7.1.2 Event #1 (May 16, 23:34 PDT) Sinusoidal Data [PQ 16]

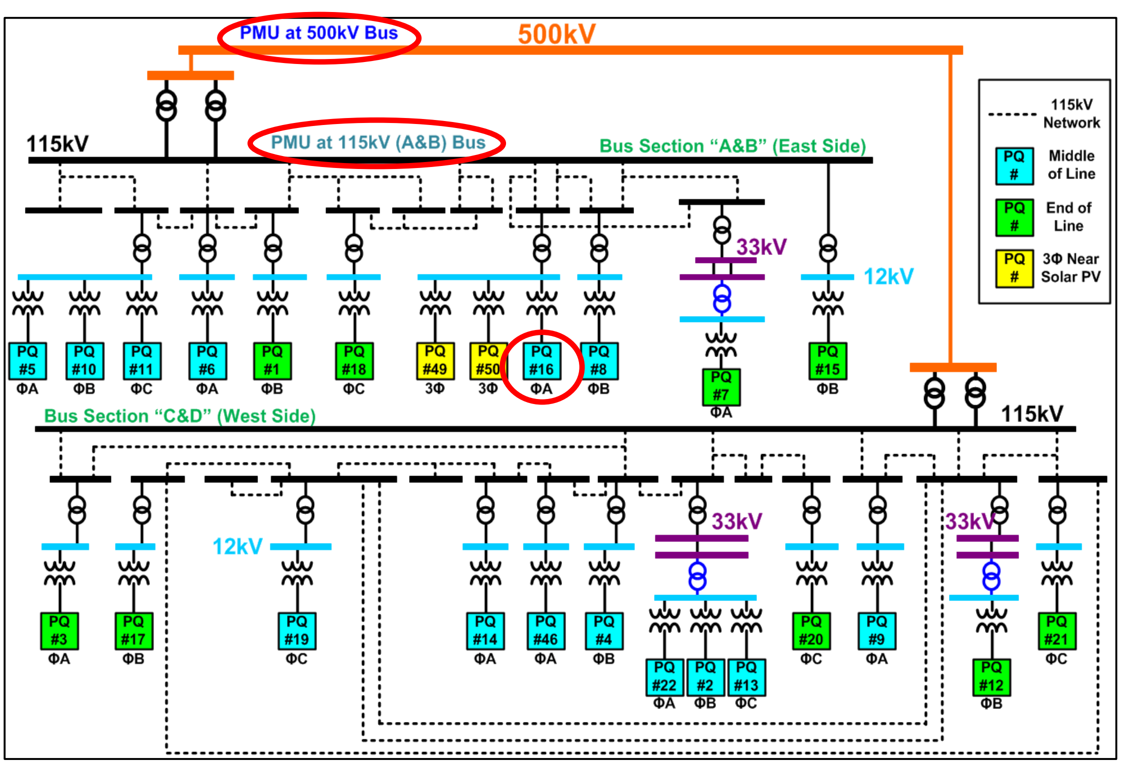

Figure 7.1.3 Event #1 (May 16, 23:34 PDT) Monitoring Locations

7.2 Event #2 (June 30, 18:49 PDT)

No information was documented by the GCC for this specific event. The RMS data for this event shown in Figure 7.2.1 exhibited the following characteristics at the monitoring location of PQ 19 on phase C of the Valley 115 kV section C&D bus:

- **Voltage recovers rather quickly without much of a delayed response**
- The voltage event appears be fairly localized as it was only captured by a PQ device at a single location with nearly no response at the sub-transmission level
- Voltage at the PCC drops to 57% of nominal and does not begin recovering until approximately 0.7 seconds later
- Real power (P) and reactive power (Q) increased significantly upon voltage recovery
  - P = 2.6X at V = 97% within 1 second after the fault
  - Q = 4.4X at V = 97% within 1 second after the fault
- The increase in load consumption from stalling following the fault does appear to be sufficient enough to induce a delayed voltage recovery
- Stalled load(s) begins dropping approximately 1 second after the voltage fault and continues until 13% of the pre-event load is lost
- The sudden increase in P & Q after the 14 second mark is likely the result of inrush from restarting load

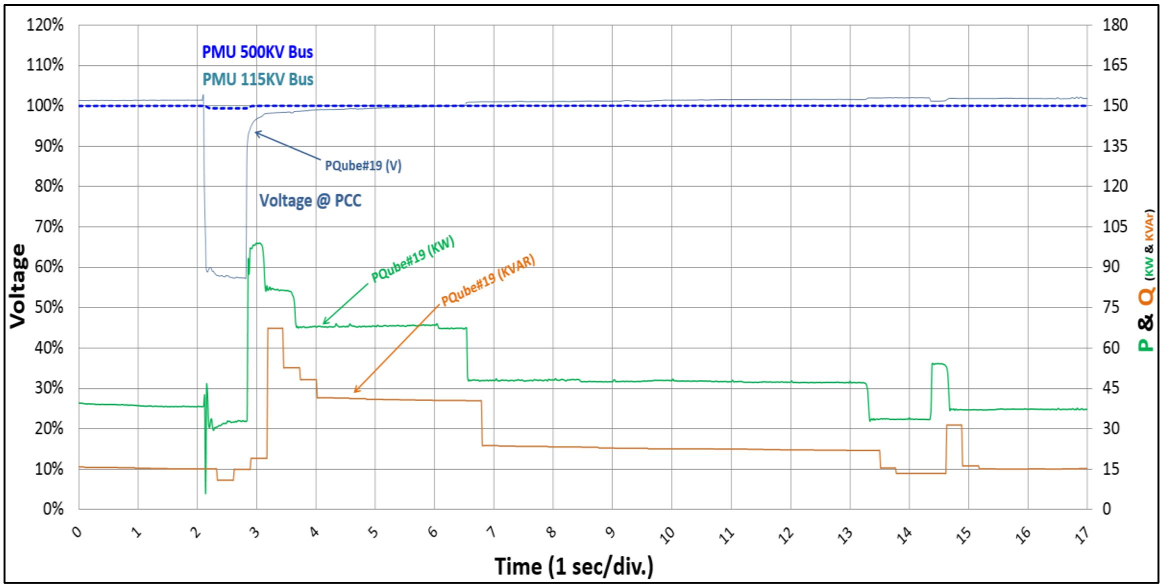

Figure 7.2.1 Event #2 (June 30, 18:49 PDT) RMS Data [PQ 19]

The sinusoidal waveform data from the PQ 19 device indicates that the fault occurred at the 90 degree angle of the Line 2 voltage waveform. The peak current values do increase slightly during this transient. However, the RMS data indicates that the condition where loads are completely stalled occurs outside the window of the recorded sinusoidal waveform data.

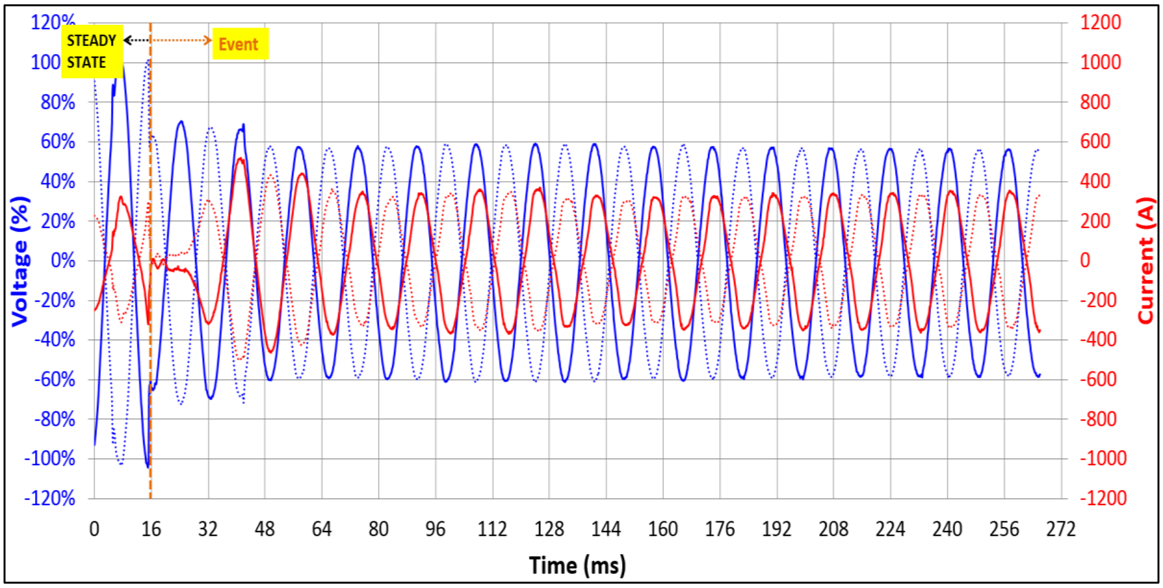

Figure 7.2.2 Event #2 (June 30, 18:49 PDT) Sinusoidal Data [PQ 19]

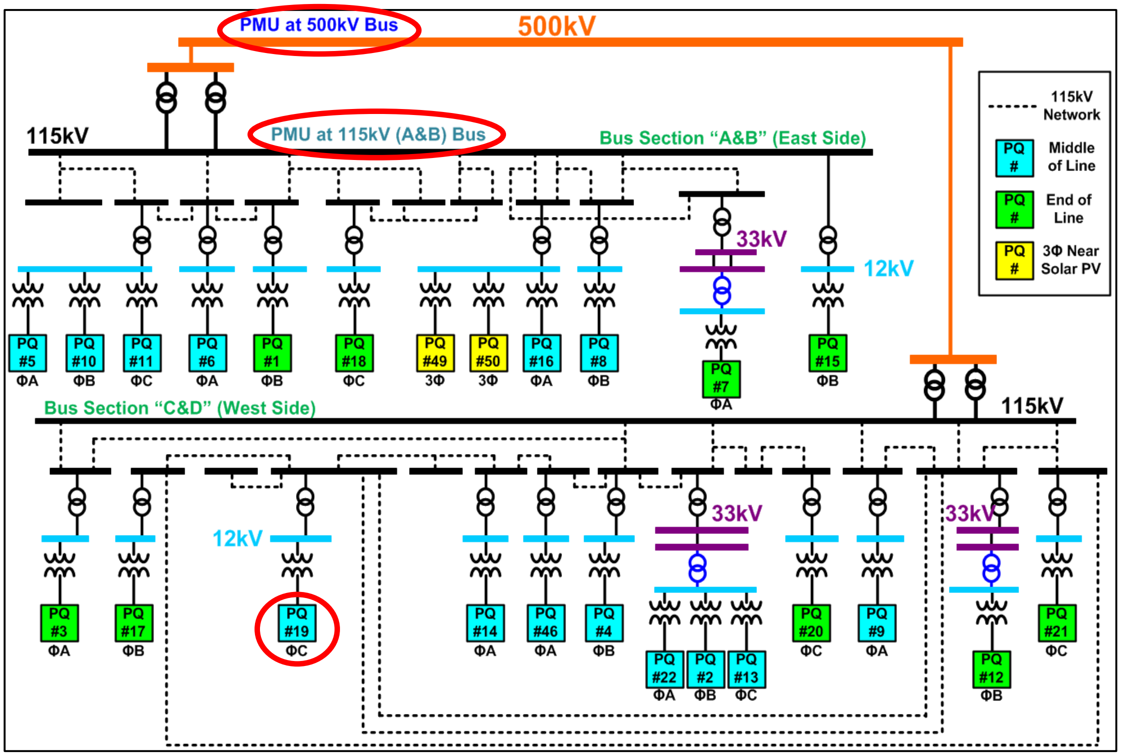

Figure 7.2.3 Event #2 (June 30, 18:49 PDT) Monitoring Locations

7.3 Event #3 (July 29, 15:15:11 PDT)

The following event was captured from PQ device 7 located on phase A in the section A&B bus. No information was documented by the GCC for this location at the specified time. The RMS data for this event shown in Figure 7.3.1 exhibited the following characteristics:

- The event caused a minor voltage deviation on the sub-transmission system as evidenced by the PMU data, but only a single PQ device captured an under-voltage profile from the monitored locations
- Voltage at the PCC drops to 95% during the first fault observed and then as low as 69% of nominal during the second fault
- After the second fault, voltage recovers to 92% with 0.5 seconds and then to nominal in another 5.5 seconds
- **No stalling behavior was observed at the monitoring location** (customers served from this padmount transformer may have not been running their A/C units)
- No over-voltage was observed after this event

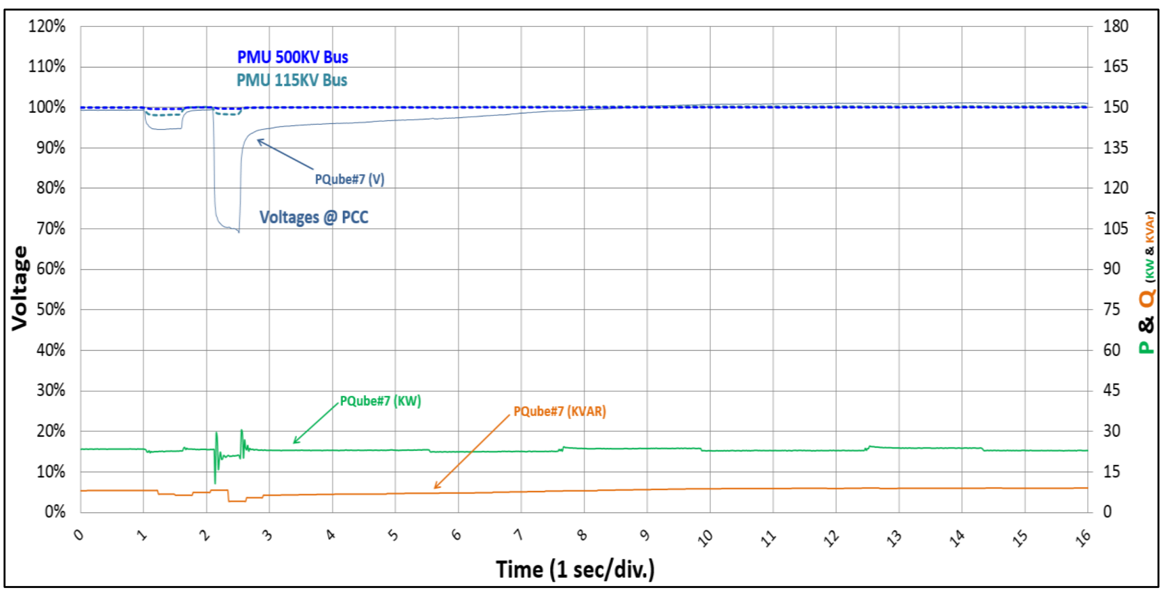

Figure 7.3.1 Event #3 (July 29, 15:15:11 PDT) RMS Data [PQ 7]

The sinusoidal waveform data from the PQ 7 device indicates that the fault occurred at the 15 degree angle of the Line 1 voltage waveform. Other than a brief increase within the first couple cycles of the transient, no significant response is observed from the current.

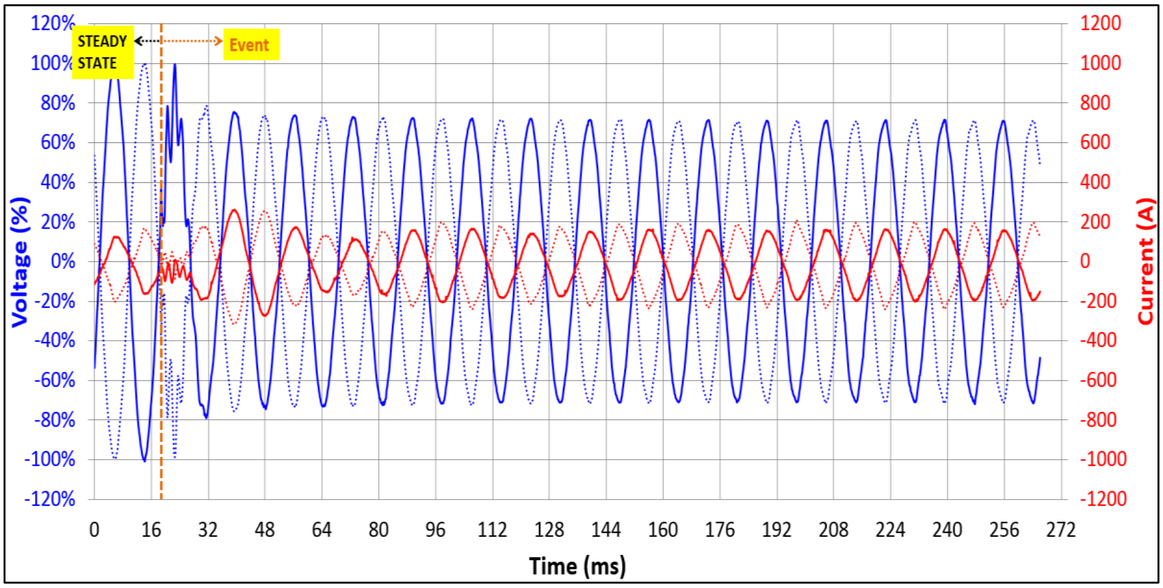

Figure 7.3.2 Event #3 (July 29, 15:15:11 PDT) Sinusoidal Data [PQ 7]

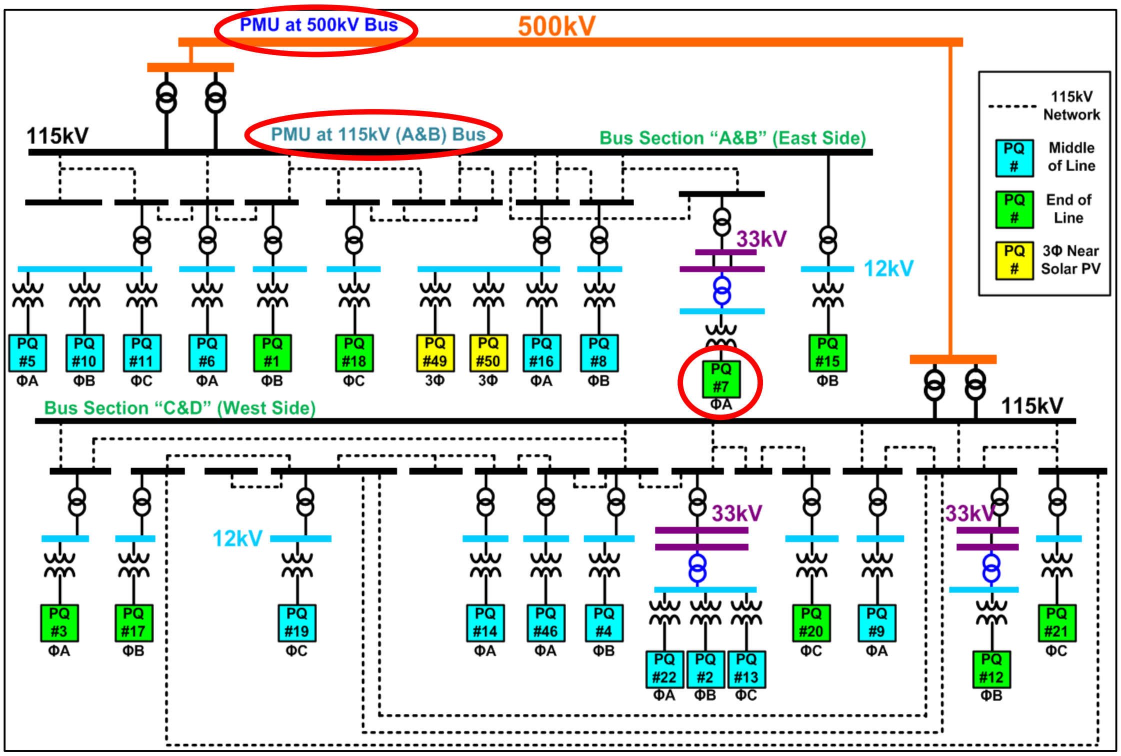

Figure 7.3.3 Event #3 (July 29, 15:15:11 PDT) Monitoring Locations

7.4 Event #4 (July 29, 15:15:27 PDT)

This event was captured from PQ device 18 located on phase C in the section A&B bus which occurred within seconds of the previous event. No information was documented by the GCC for this location at the specified time. The RMS data captured during this event, as shown in Figure 7.4.1, reveals the following:

- The event caused a minor voltage deviation on the sub-transmission system as evidenced by the PMU data, but now a different PQ device captured an under-voltage at the PCC
- Voltage at the PCC decreases in steps, dropping as low as 62% of nominal
- **No delayed voltage recovery or stalling observed during this event** (customers served from this padmount transformer may have not been running their A/C units)

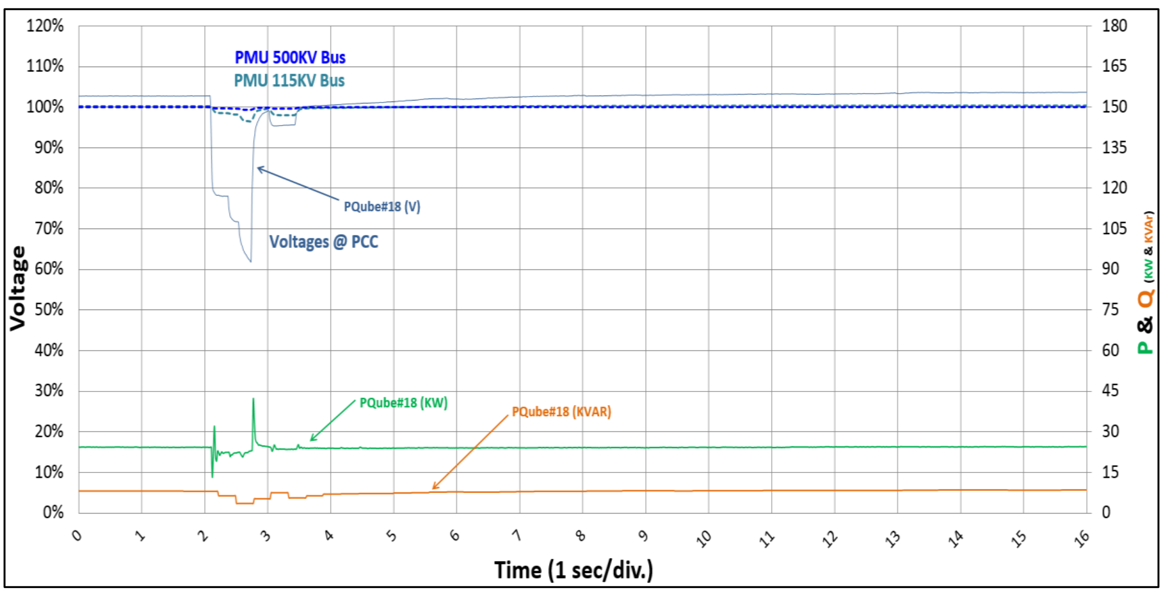

Figure 7.4.1 Event #4 (July 29, 15:15:27 PDT) RMS Data [PQ 18]

The sinusoidal waveform data from the PQ 18 device failed to capture the beginning of the fault. Additionally, no stalling behavior was observed during this event resulting in no significant response from the current waveforms.

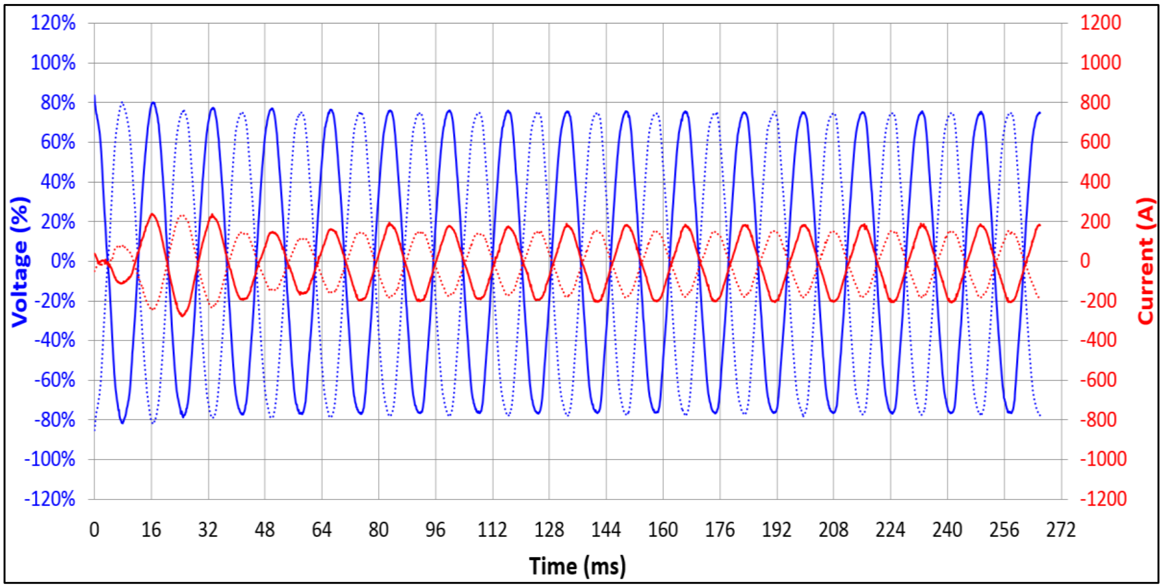

Figure 7.4.2 Event #4 (July 29, 15:15:27 PDT) Sinusoidal Data [PQ 18]

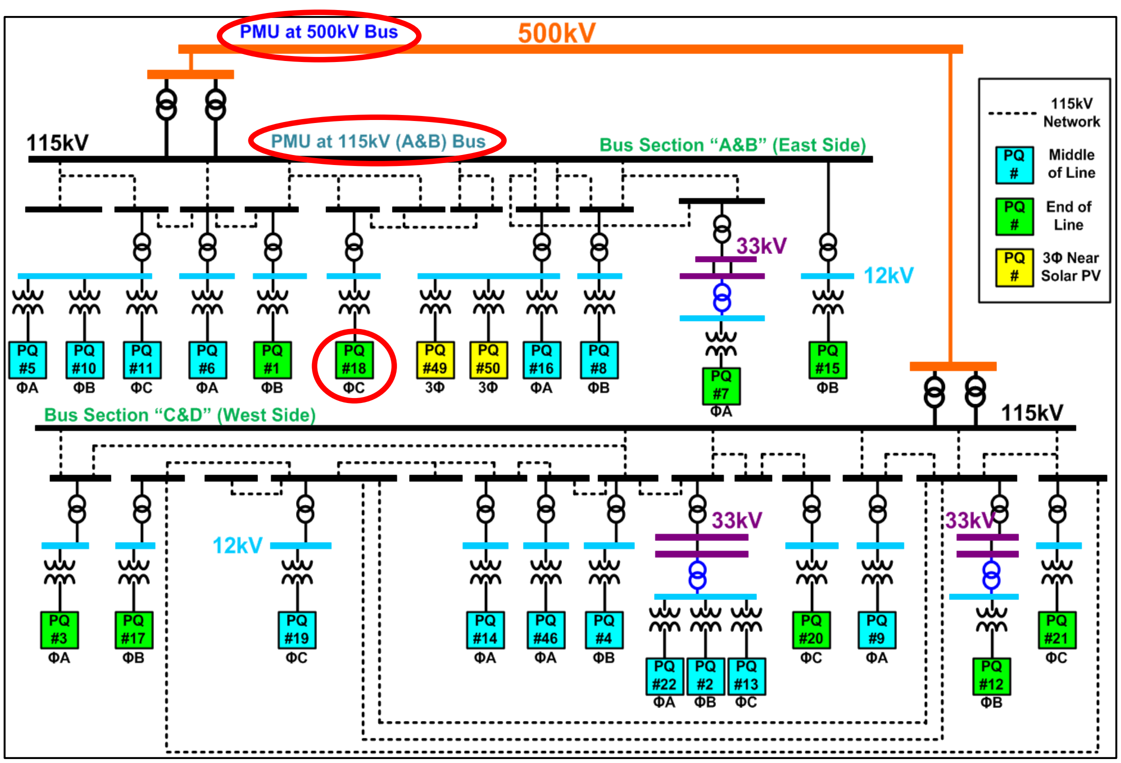

Figure 7.4.3 Event #4 (July 29, 15:15:27 PDT) Monitoring Locations

7.5 Event #5 (August 2, 10:41 PDT)

The following event was captured from PQ device 1 located on phase B on a 12 kV circuit from the Valley section A&B bus. No information was documented by the GCC for this location at the specified time. The RMS data for this event shown in Figure 7.5.1 exhibited the following characteristics:

- The event captured did influence the sub-transmission system as observed by the PMU data captured in the Valley region. However one of the installed PQ devices captured an under-voltage recovery event at the distribution level
- The secondary voltage profile implies that voltage decreased to 41% during the initial fault. As voltage began recovering, another fault resulted in voltage dropping down to 40% of nominal.
- PMU data indicates that the 115kV sub-transmission voltage dropped as low as 88% of nominal while the 500kV transmission voltage had a minor 2% deviation
- Real power (P) and reactive power (Q) momentarily increased as such
  - P = 2.1X at V = 41% within 1 second after the fault
  - Q = 3.0X at V = 83% within 1 second after the fault
- The real and reactive power at this padmount installation monitoring site **do not appear to have sufficient load stalling**
- The voltage profile suggests that this could possibly be a localized FIDVR event with load stalling on adjacent padmount transformers (not being monitored) and/or circuits where there may be more air conditioner load. However, this cannot be confirmed since voltage data from neighboring padmounts or circuits was not observed at this resolution.

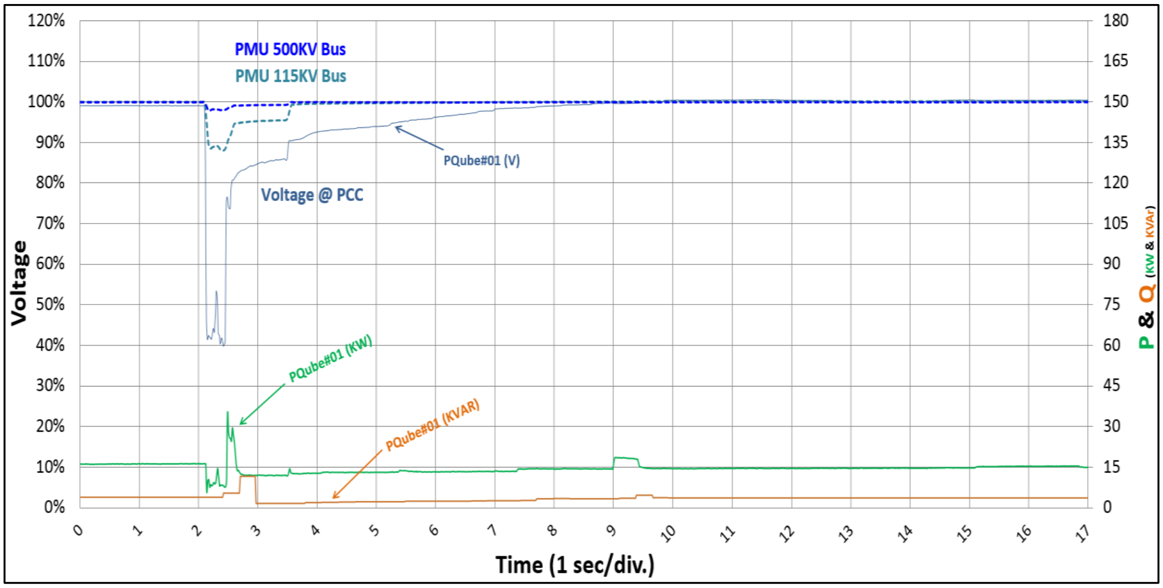

Figure 7.5.1 Event #5 (August 2, 10:41 PDT) RMS Data [PQ 1]

The sinusoidal waveform data from the PQ 1 device indicates that the fault occurred at the 10 degree angle of the Line 1 voltage waveform. Immediately after the fault, the current waveform begins leading voltage before returning to a lagging condition a couple cycles later. No stalling is observed from the sinusoidal waveforms.

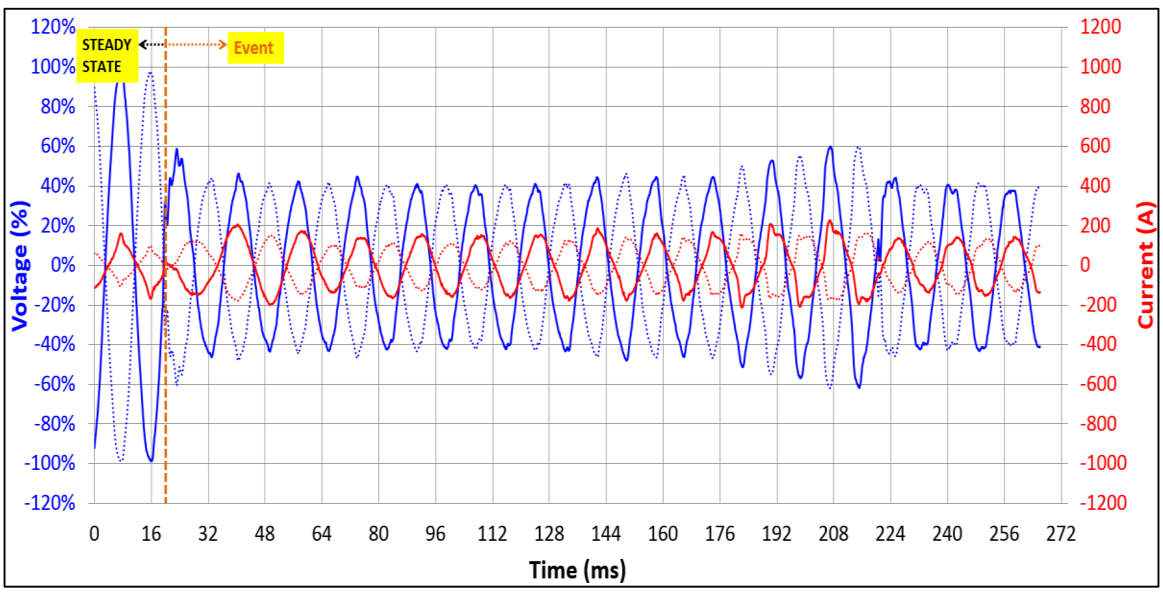

Figure 7.5.2 Event #5 (August 2, 10:41 PDT) Sinusoidal Data [PQ 1]

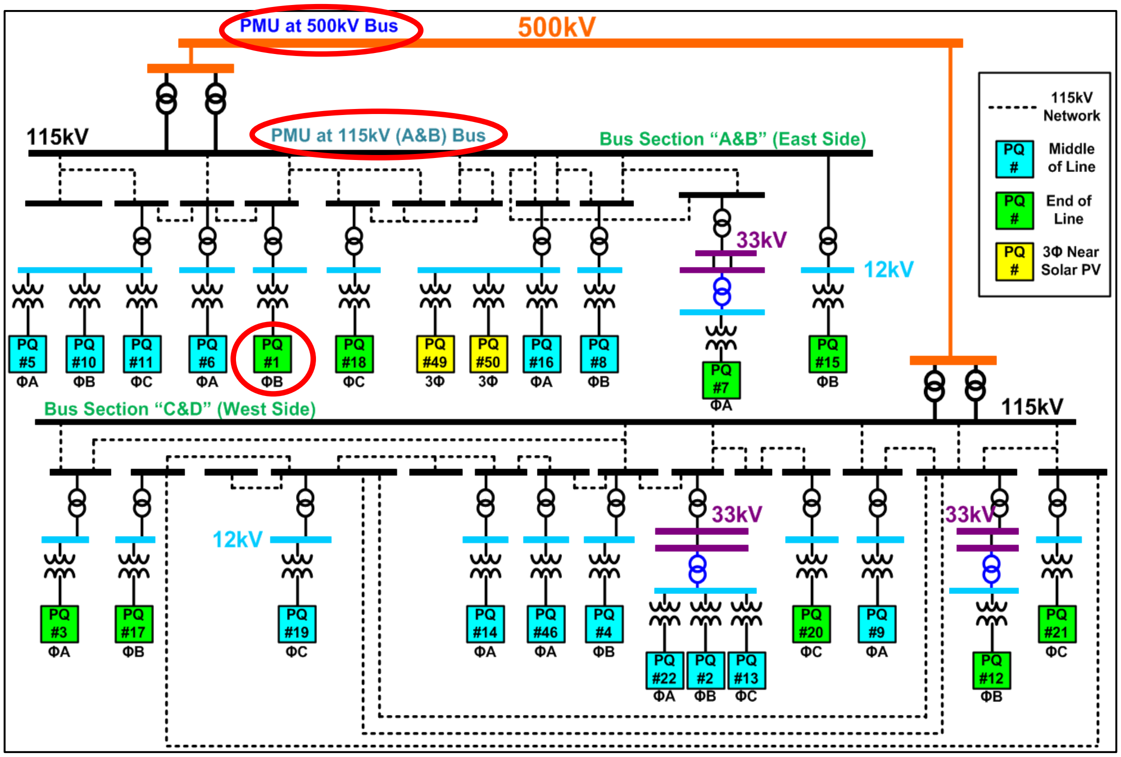

Figure 7.5.3 Event #5 (August 2, 10:41 PDT) Monitoring Locations

7.6 Event #6 (August 11, 13:54 PDT)

This event was captured from PQ device 3 located on phase A of a circuit within the section C&D bus. Records from the Grid Control Center (GCC) indicate that two 115 kV lines out of a single substation relayed and reclosed with the cause under investigation. The RMS data for this event shown in Figure 7.6.1 exhibited the following characteristics:

- Voltage is decreased to 0% for over two seconds as observed at the monitoring location
- After reclosing occurs, voltage takes approximately another 5 seconds to fully recover
- Although the under-voltage event was extremely low, **it did not provoke load stalling at the monitoring location** despite temperatures in the mid 80°s
- No significant over-voltage behavior was captured during this event

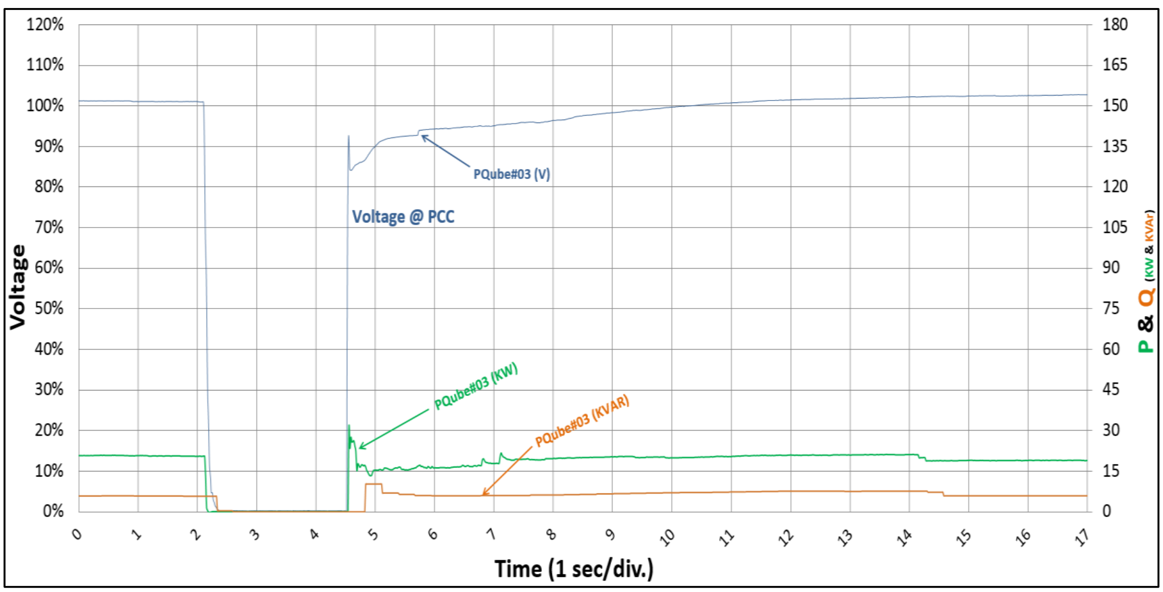

Figure 7.6.1 Event #6 (August 11, 13:54 PDT) RMS Data [PQ 3]

The sinusoidal waveform data from the PQ 3 device indicates that the fault occurred at 0 degree angle (or zero crossing) of the Line 1 voltage waveform. Voltage falls to zero in several cycles and recovery is not captured in the limited window (approximately 16 cycles) of the sinusoidal event data.

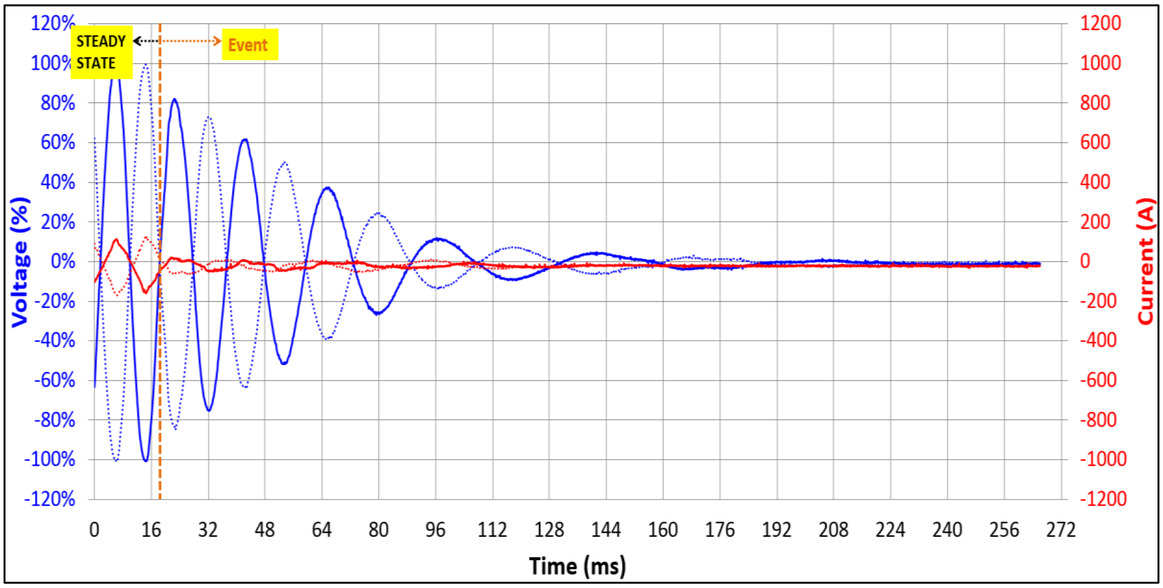

Figure 7.6.2 Event #6 (August 11, 13:54 PDT) Sinusoidal Data [PQ 3]

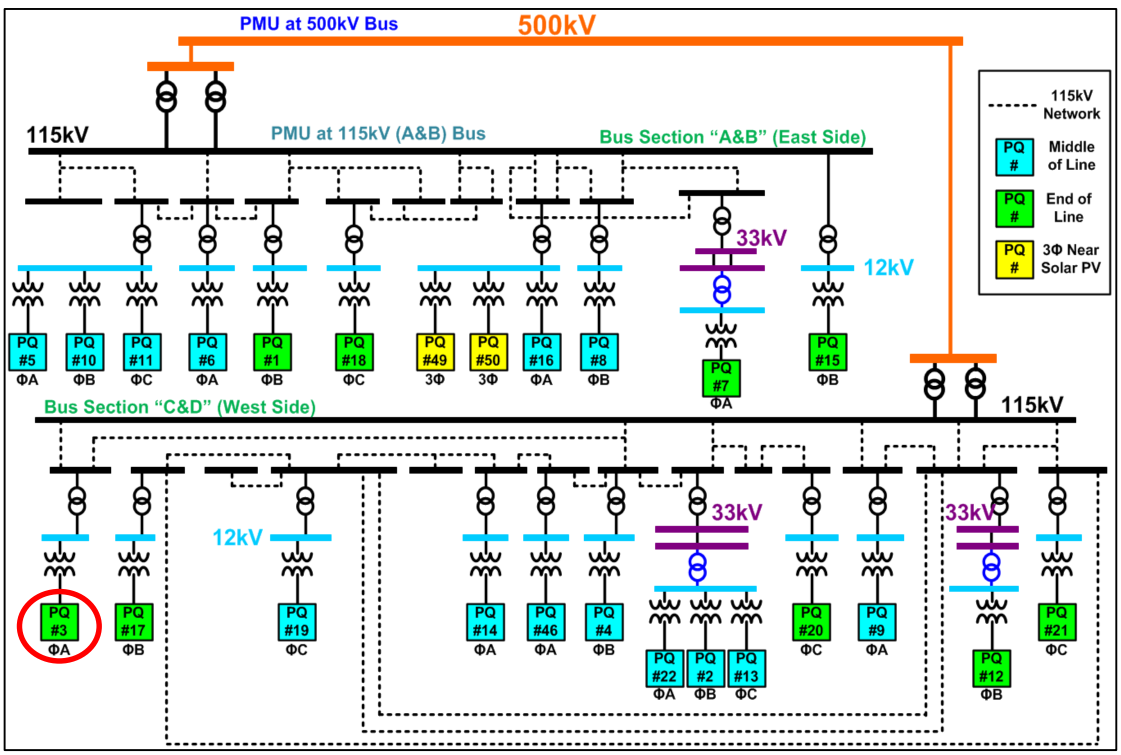

Figure 7.6.3 Event #6 (August 11, 13:54 PDT) Monitoring Locations

7.7 Event #7 (September 16, 14:36 PDT)

The following event was captured from PQ devices 14 and 17 located on different phases within the section C&D bus of the Valley system. The GCC reported that a 115 kV line relayed during a storm and numerous distribution lines relayed and reclosed resulting in approximately 50 MW of voltage sensitive load disconnected itself during the event. The RMS data for this event shown in Figure 7.7.1 exhibited the following characteristics:

- The event spread through more than one of the distribution systems as evidenced by the multiple PQ device recordings
- Voltage decreased as low as 55% of nominal for PQ 17 and 75% for PQ 14
- After the fault, the voltage took nearly 6.5 seconds to recover to it pre-event values at the PCC for PQ 17
- Despite the minor voltage recovery profile, **there does not appear to be any load stalling behavior at either of the two monitoring locations**
- The voltage profile and GCC report imply stalling may have occurred at adjacent padmount locations and/or adjacent circuits without PQ devices. However, this cannot be confirmed since voltage data from neighboring padmounts or circuits was not observed at this resolution.

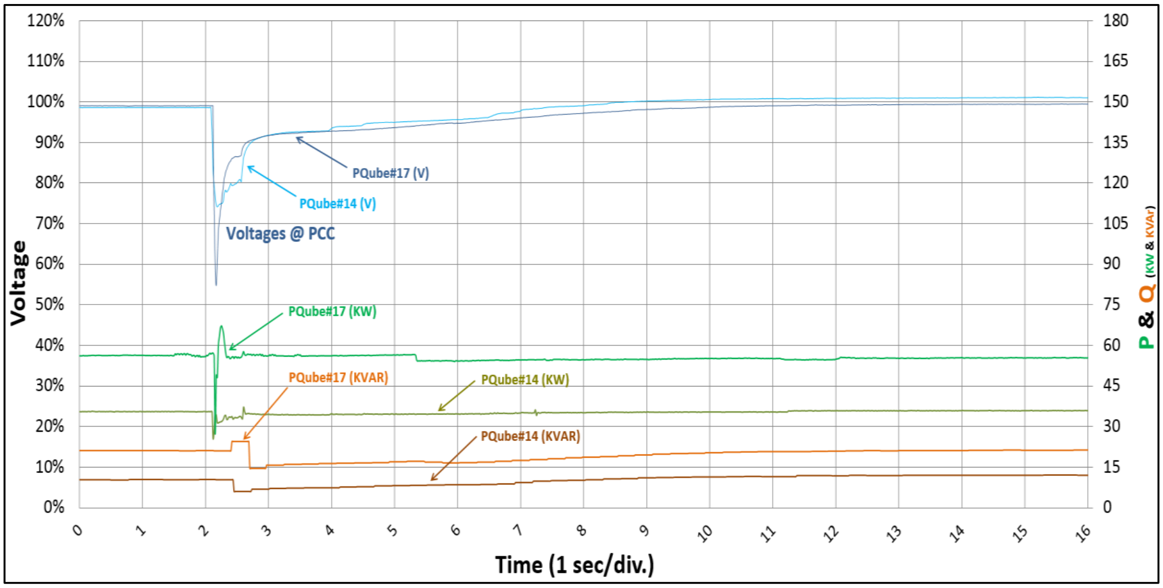

Figure 7.7.1 Event #7 (September 16, 14:36 PDT) RMS Data [PQ 14 and 17]

The sinusoidal waveform data from the PQ 17 device indicates that the fault occurred near the zero crossing of the voltage waveform. Although peak current increases momentarily within several cycles following the fault, it does not appear that the sinusoidal data captures stalled loads.

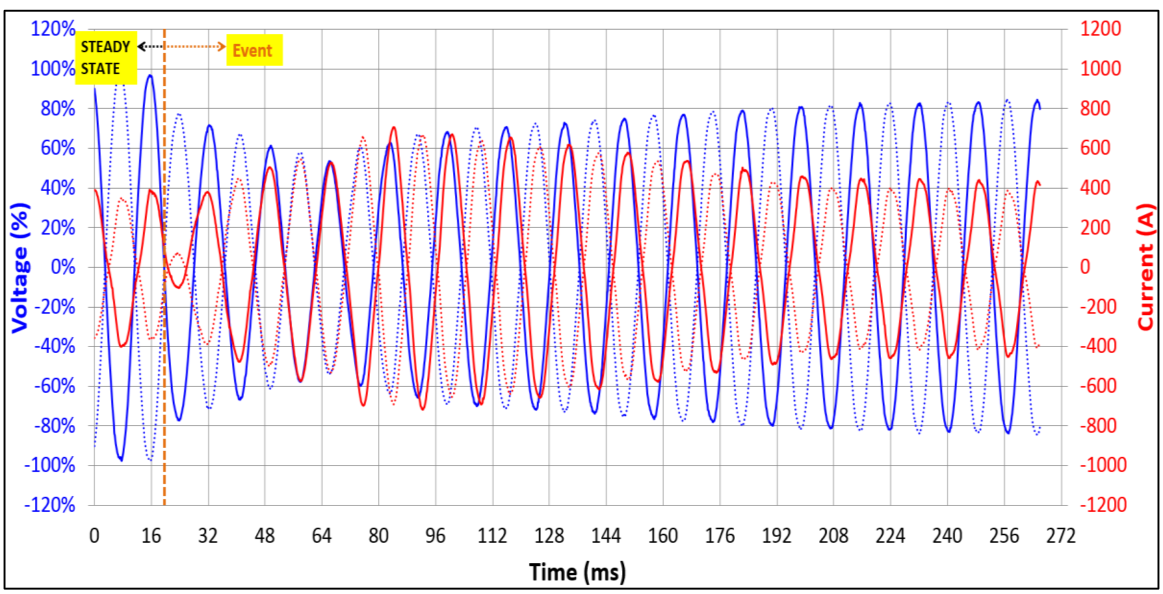

Figure 7.7.2 Event #7 (September 16, 14:36 PDT) Sinusoidal Data [PQ 17]

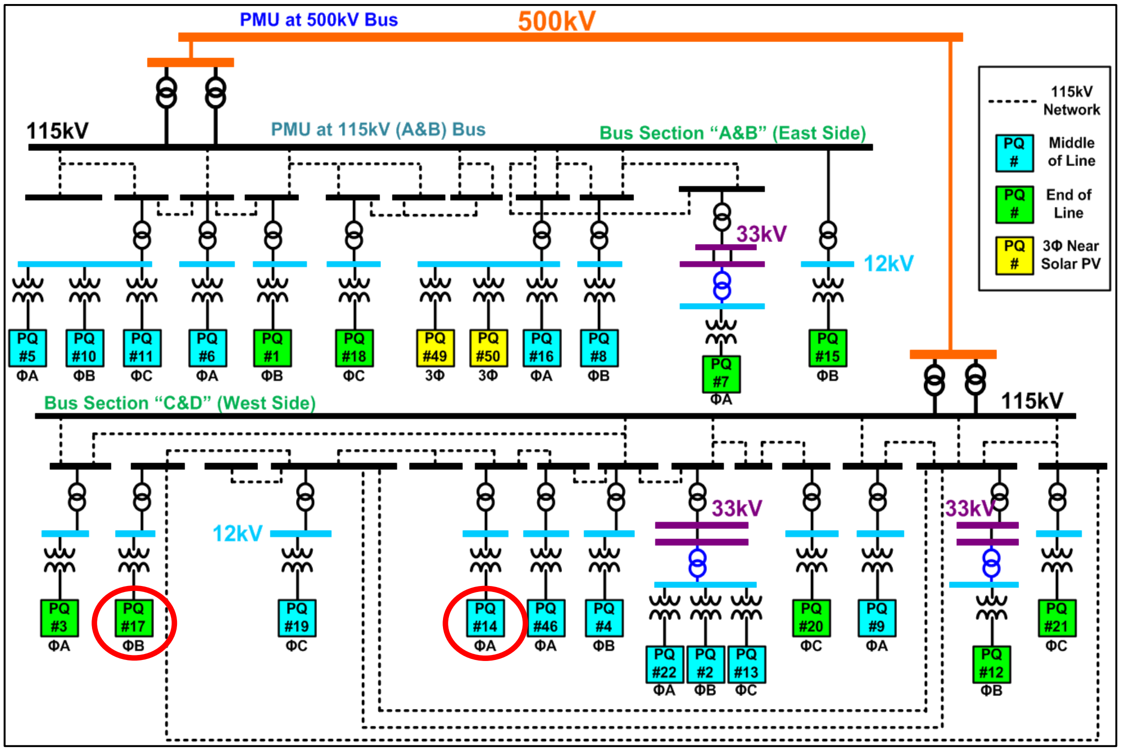

Figure 7.7.3 Event #7 (September 16, 14:36 PDT) Monitoring Locations

7.8 Event #8 (October 24, 15:34 PDT)

The following event was captured from PQ device 8 located on phase B of a circuit within the section A&B bus in Valley. GCC records state that a 115 kV line relayed when a remote controlled glider contacted conductor and flashover occurred. The RMS data for this event shown in Figure 7.8.1 exhibited the following characteristics:

- **No significant delayed voltage recovery** was recorded during this event
- Voltage drops to as low as 46% of nominal as observed by PQ 8 at the PCC
- It took approximately 3 seconds for voltage to recover (recovered to 95% of nominal within the first second)
- Real power (P) and reactive power (Q) increased as such
  - P = 2.3X at V = 96% within 1 second after the fault
  - Q = 3X at V = 96% within 1 second after the fault
- Possibly stalled load(s) disconnect and/or restart within 2 seconds of the fault
- This event caused loss in load of approximately 25% to 30% in load after fault
- Although this undervoltage transient may have stalled load on a single circuit, it did not provoke a FIDVR event, likely due to a low amount of distributed A/C load

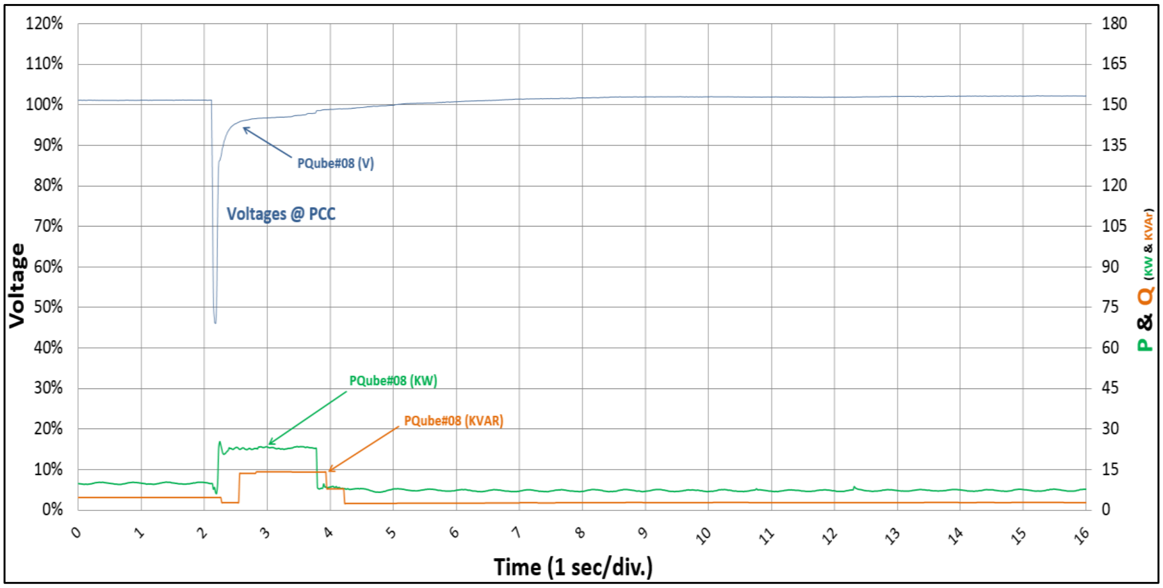

Figure 7.8.1 Event #8 (October 24, 15:34 PDT) RMS Data [PQ 8]

The sinusoidal waveform data from the PQ 8 device indicates that the fault occurred at the 80 degree angle of the Line 2 voltage waveform. The current is nearly 75 amps-peak before the event and as high as 220 amps-peak within the window of the sinusoidal data captured.

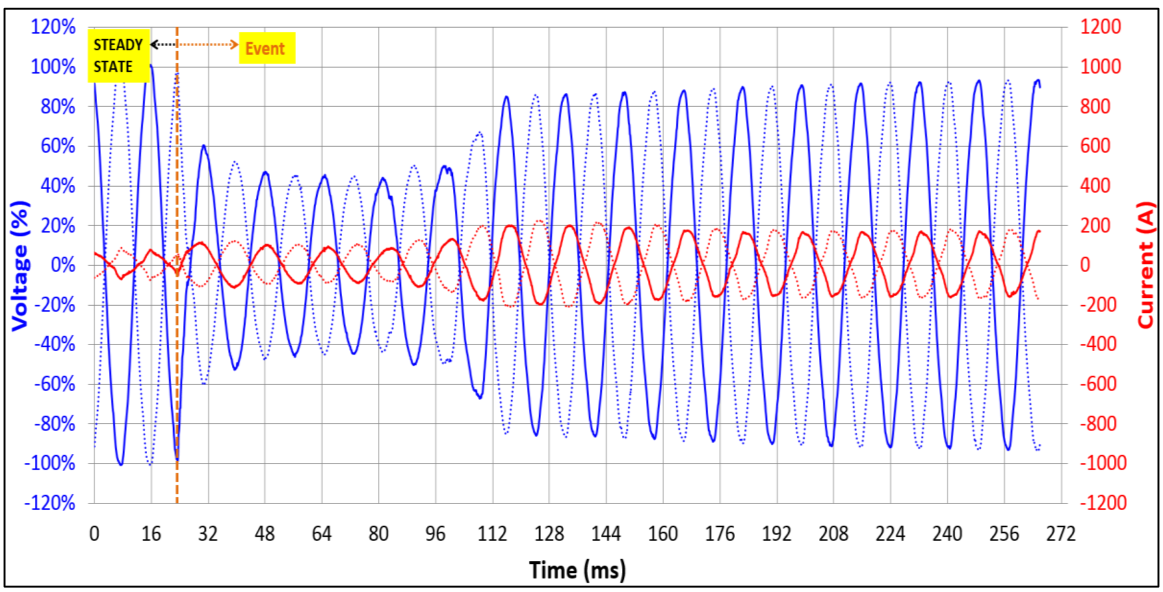

Figure 7.8.2 Event #8 (October 24, 15:34 PDT) Sinusoidal Data [PQ 8]

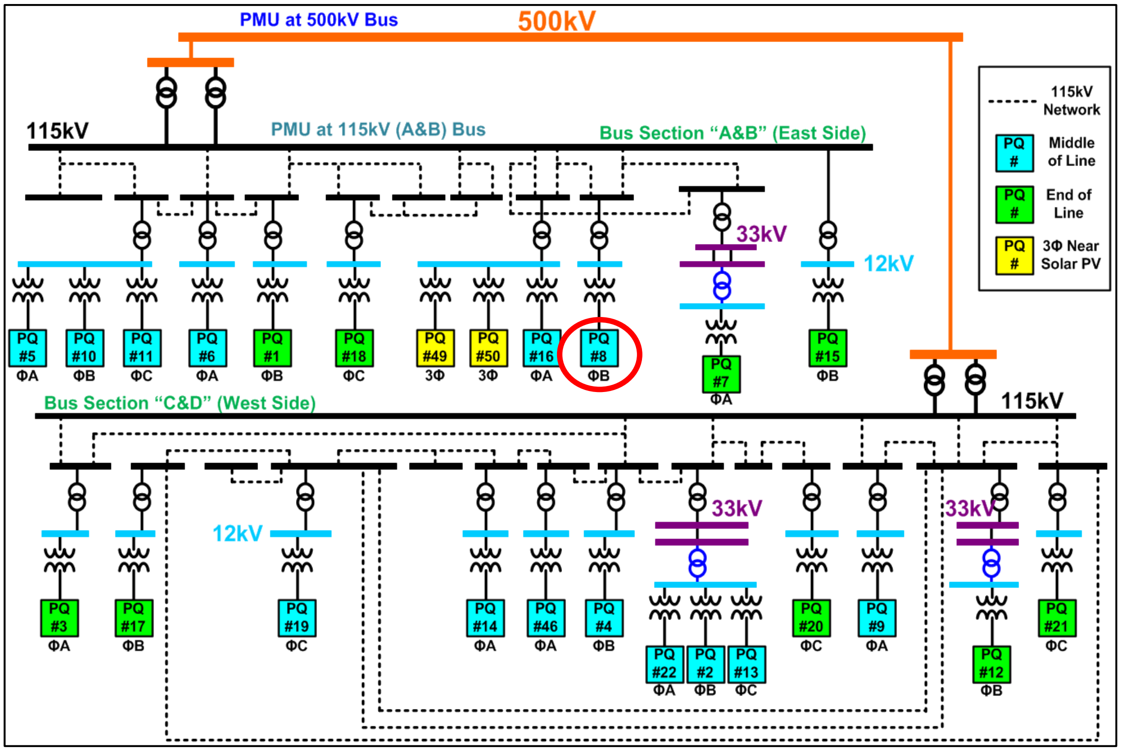

Figure 7.8.3 Event #8 (October 24, 15:34 PDT) Monitoring Locations

8.0 CONCLUSIONS AND RECOMMENDATIONS

The number of FIDVR events captured during summer 2014 appears to be lower than the amount captured in prior years. Only two of the events recorded are classified as distribution level FIDVR events. Another eight voltage events with FIDVR related attributes were included for analysis. These eight additional events were documented based on characteristics observed from the RMS event data that include:

- Load(s) stalling without significant delayed voltage recovery
- Delayed voltage recovery without evidence of stalled loads
- Abnormal voltage fault/recovery profiles

One issue observed with the sinusoidal waveform event data was the length of the data recorded. The sampling rate of the sinusoidal data was increased from 32 samples/second to 128 samples/second in previous years to capture harmonic snapshot data. As a result the length of the time captured reduced from approximately 64 cycles to 16 cycles. While this typically is not an issue for capturing A/C stalling which normally occurs within the first few cycles of the fault, several events resulted in stalling behavior taking place outside of the recorded window. This should be kept in mind for future monitoring with the same devices.

Table 7.0.1 below notes where the faults were initiated on the voltage waveforms for each of the events captured.

	Fault Initiated		
Event #	**Voltage Waveform Angle**	**Reading at Line**	**Comments**
1	80°	L1	
2	40°	L1	
Additional Voltage Events			
1	50° / 100°	L1	
2	90°	L2	
3	15°	L1	
4	----	----	PQ recorder failed to record the beginning of the fault
5	10°	L1	
6	0°	L1	
7	0°	L2	
8	80°	L2	

Table 7.0.1 Fault Initiation on Voltage Waveform

This data may not directly correlate to the triggering of FIDVR events. However, it has been suggested that when an instantaneous fault is applied at voltage zero crossing, A/C motors stall faster because of the large electrical braking torque. Faults that occur at the peak of the sinusoidal waveform are thought to require lower voltages to induce motor stalling. Unfortunately most of the events captured do not display load stalling or, as previously mentioned, stalling behavior takes place outside of the recorded window for the sinusoidal waveform data.

Over the course of this multiyear effort from 2011 to 2014, it has been made evident that FIDVR events do occur more often than previously expected during monsoon weather conditions. Based on the events documented in this report as well as those recorded on the distribution system during prior summer seasons, the following conclusions have been met:

- Localized FIDVR events can occur and may not appear in PMU data (captured in the transmission/sub-transmission network)
- Additional RAC units can potentially stall in the middle of a FIDVR event, suggesting a cascading effect
- Sinusoidal data has suggested that:
    - RAC units can stall very fast, in about 1 electrical cycle
    - RAC units stall no matter where the fault began in the voltage waveform
    - The first cycle of the FIDVR events can result in current leading the voltage, but afterwards goes to the pre-event condition load status of current lagging voltage

Another important observation, also mentioned in previous iterations of this report[1,2], is that all the per-unitized voltages in the network (transmission, sub-transmission, and customer PCC) are the same at steady-state, but their values vary significantly immediately after the FIDVR event begin indicating differences in RAC load and system impedance during the FIDVR

[1] Bravo, Richard J., and Steven Robles. 2012 FIDVR Events Analysis: Valley Distribution Circuits. SCE, 2013.
[2] Bravo, Richard J., and Steven Robles. 2013 FIDVR Events Analysis on Valley Distribution Circuits. SCE, 2013.

events. This is relevant to engineers trying to determine the proper load composition for their system studies. Prior sensitivity and validation studies performed at SCE required the modeler to set WECC’s composite load model parameter for penetration of RAC load lower than what is actually connected to replicate a system event. This mismatch of RAC penetration (percent of total load) may be due to the distribution system impedance between the sub-transmission system and PCC. The data collected from these events can support the matching of system impedance values, which may result in more accurate RAC penetration values in the load model.

Although no significant events were captured by the PQubes located near renewable generation, utilities have suggested that FIDVR events may have negative impacts on neighboring solar photovoltaic (PV) generation sites. This is due to the solar PV standards with strict abnormal voltage protection criteria that did not allow voltage ride-through (VRT) capabilities. Ultimately, this would cause existing solar PV generation to disconnect during FIDVR events. However, the adoption of recent amendments to inverter interconnection standards (IEEE 1547a and California Rule 21) will prevent future instances of these negative impacts.