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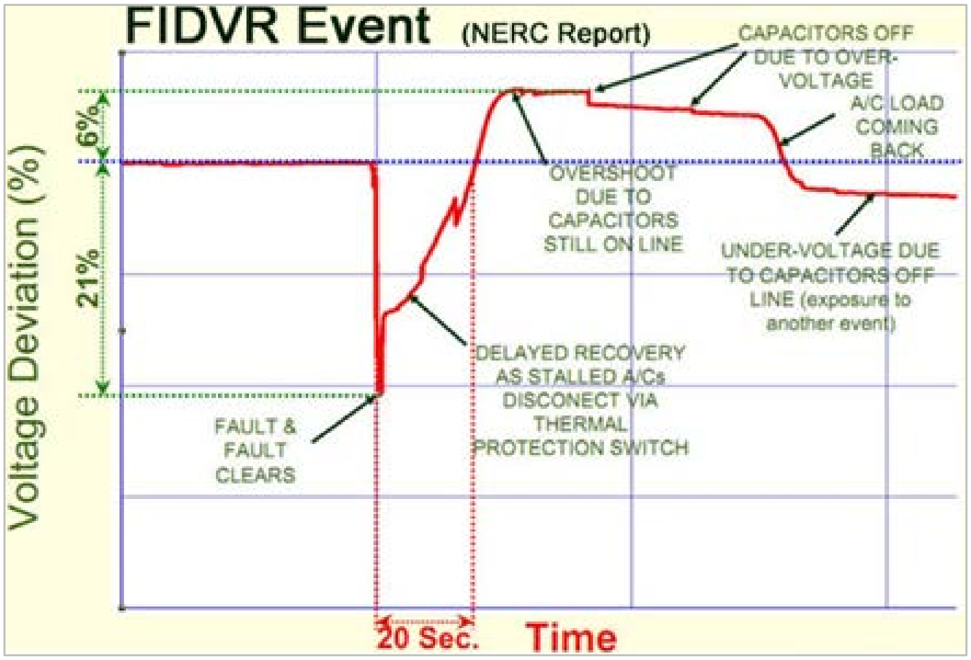
2013 FIDVR Events Analysis on Valley Distribution Circuits



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December 30, 2013

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The authors acknowledge the additional support of LBNL independent consultant, John Kueck, and SCE intern Shruthi Sama who provided valuable contribution in the development of this procedure.

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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 shown in Figure 1.0.1 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, 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.

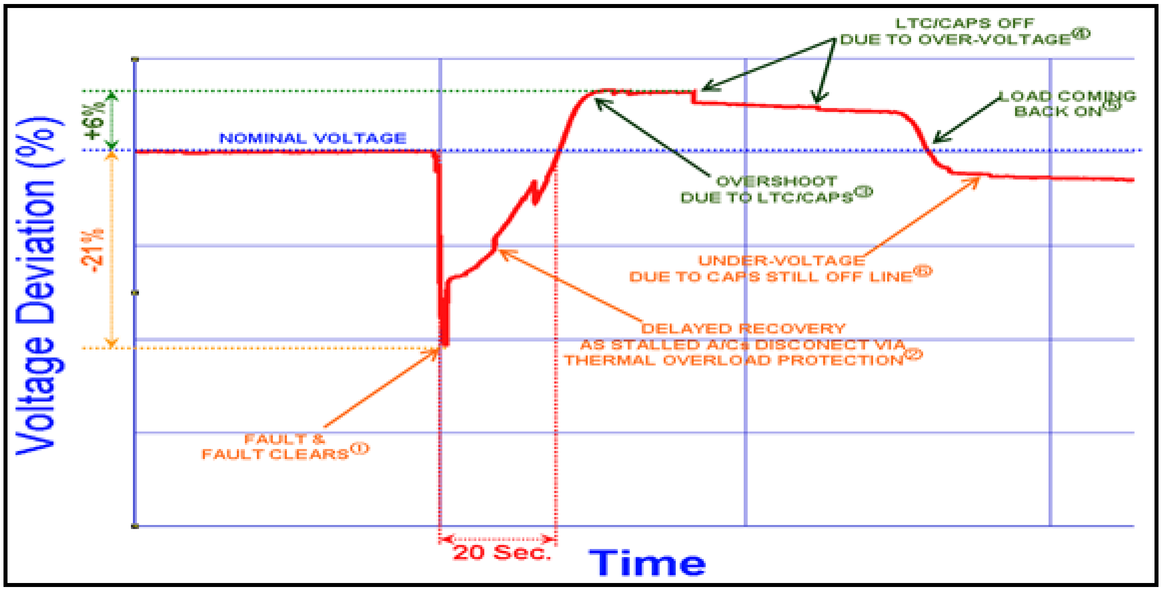

Figure 1.0.1 FIDVR Anatomy

In most cases, these events are localized and do not cascade or spread throughout the transmission system to cause outages. There is concern that these faults should 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 investigating FIDVR events. Additionally, its members tested 27 RAC units during 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 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 when 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. The rough estimation of air conditioner load during summers at valley is approximately 60% as shown in Figure 1.0.2. It shows that during summer times compared to winter times, there is an increment of 300 percent. The majority of this load is thought to be air conditioner load.

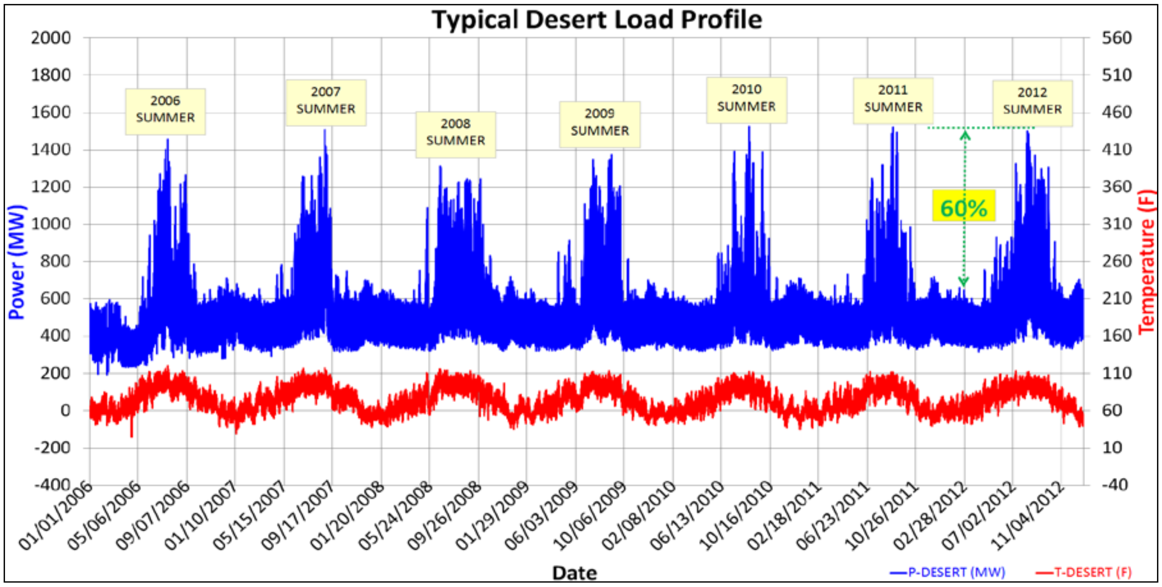

Figure 1.0.2 Valley Load Profile (2006 thru 2012)

2.0 OBJECTIVE

In an effort to examine the detailed characteristics of FIDVR events in distribution circuits, Southern California Edison (SCE) installed 23 power quality (PQ) recording devices on 18 of its Valley Substation's 24 subtransmission circuits that serve the utility's residential and commercial customers. In addition, 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) recorder to be installed in the field, specifically distribution transformers, as shown in Figure 3.0.1. The power quality recording devices in this set up 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, when an event is triggered, both:

- Root mean square (RMS) and
- Sinusoidal waveforms

The data is recorded on to a secure digital (SD) memory card for easy access and removal. The recorded data is captured and translated into comma separated values (csv) file format.

To accurately record the FIDVR events, the PQ device's trigger parameters were set up as follows:

- Under-voltage triggering threshold at 80%
- Over-voltage triggering threshold at 110%
- RMS event data captured at 1 sample/cycle (for approximately 17 seconds)
- Sinusoidal waveform event data captured at 128 samples/cycle (for approximately 16 cycles)

In addition to the FIDVR event capturing, the PQ devices were set to record steady state data every minute. This data may later be used to assess the daily load performance.

Every device was equipped with an uninterruptible power supply (UPS) for up to nine minutes so that will record during events of low voltage without compromising the data. A circuit breaker was added for 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: 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
- Enclosure

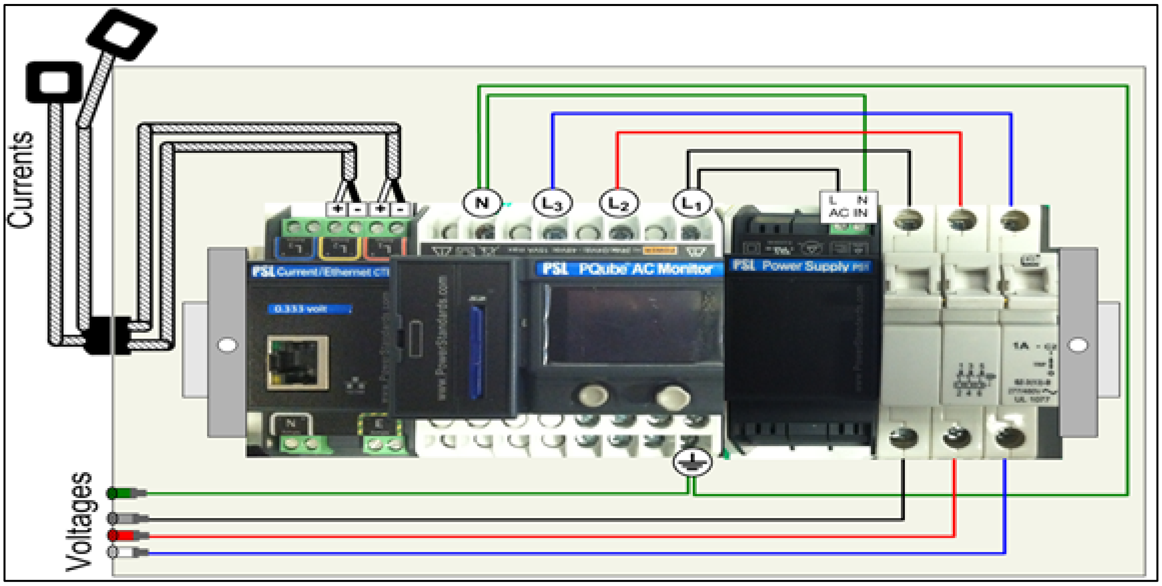

Figure 3.0.1 SCE PQ Recorders Setup

4.0 POWER QUALITY RECORDER 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.

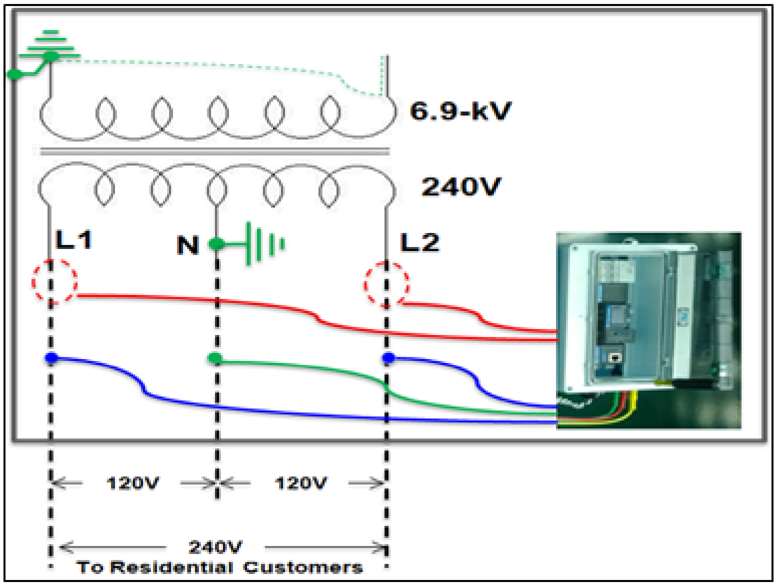

Figure 4.0.1 PQ Recorder Pad Mount Transformer Installation Diagram

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.

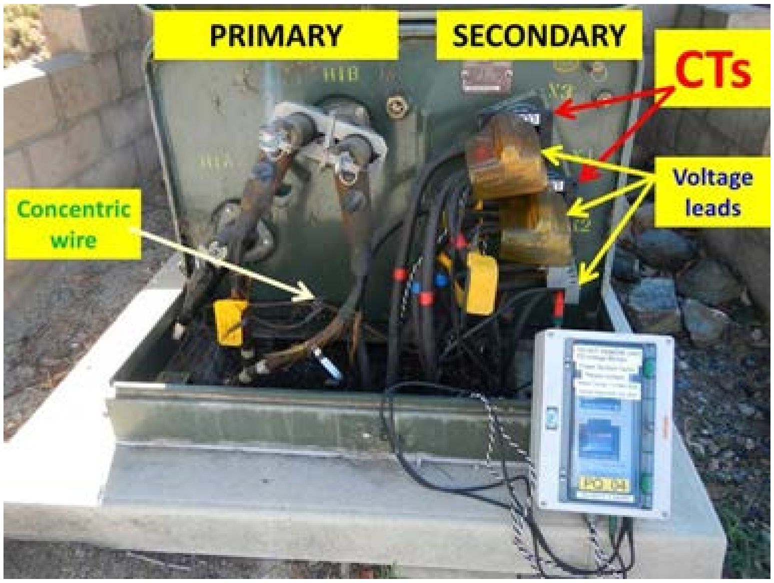

Figure 4.0.2 PQ Recorder Field Installation in a Pad Mount Transformer

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 another 115kV circuit in the Valley system. Similar to the previous installations, this device was placed in a distribution pad-mount transformer serving residential load. Additionally, 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 multiple terminal blocks to connect the voltage leads and CTs for measurements (Phase A, Phase B, Phase C and neutral rated at 208V line-to-line).

Table 4.0.1 provides the PQ installation list; two (PQ 49 and 50) were installed in a distribution circuit serving commercial loads that has an 8MW solar PV rooftop plant.

PQ Recorder		**Location on Circuit (Middle of Line or End of Line)**	**# of Customers in 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	N/A
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	N/A
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	N/A

Table 4.0.1 Valley PQ Locations Information

5.0 POWER QUALITY RECORDERS DISTRIBUTION 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 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 busses 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 transform the voltage down from 6.9 kV to 240 V 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 (240 V) 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 each monitor all three phases on a 12kV circuit with commercial solar PV generation. The 12kV 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.

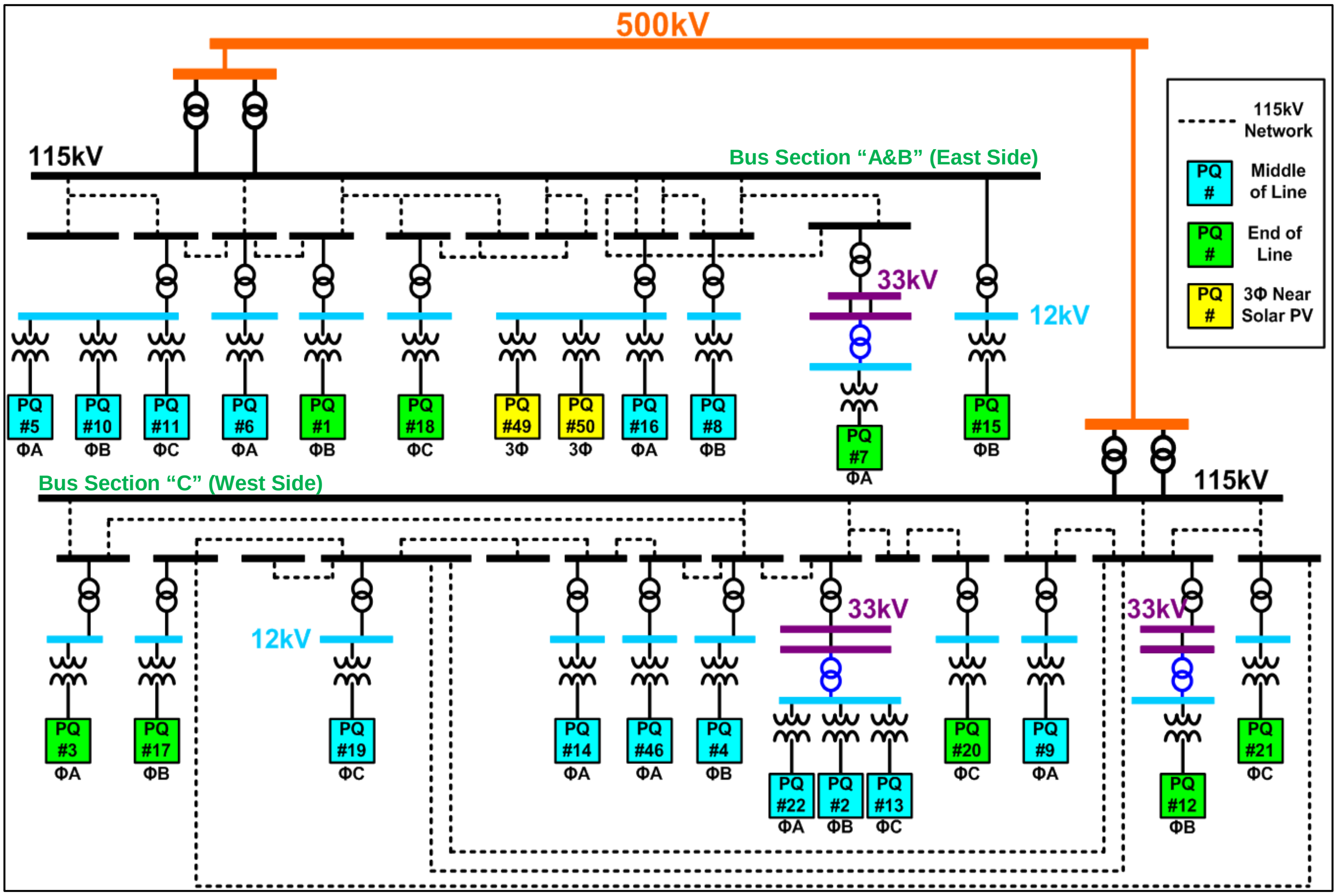

Figure 5.0.1 Valley PQ Locations Diagram

6.0 SUMMER 2013 DISTRIBUTION FIDVR EVENT ANALYSIS

The events analyzed for this study were recorded throughout the summer of 2013. These devices where installed in June and removed in November. 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.

6.1 Event #1 (June 28, 14:44 PDT)

The RMS data for Event #1 shown in Figure 6.1.1 exhibits these characteristics:

- The event spread through the distribution system as evidenced by the multiple PQ device recordings at different locations
- A fault brought the voltage down as low as 46% where RACs stalled in several distribution circuits
- Both 500 kV and 115 kV PMU signals only show a 1% voltage deviation.
- The various circuits took approximately 9 seconds respectively for voltage to recover to steady-state
- The loss of the load provoked an overvoltage as high as 14% above steady-state on the distribution circuits

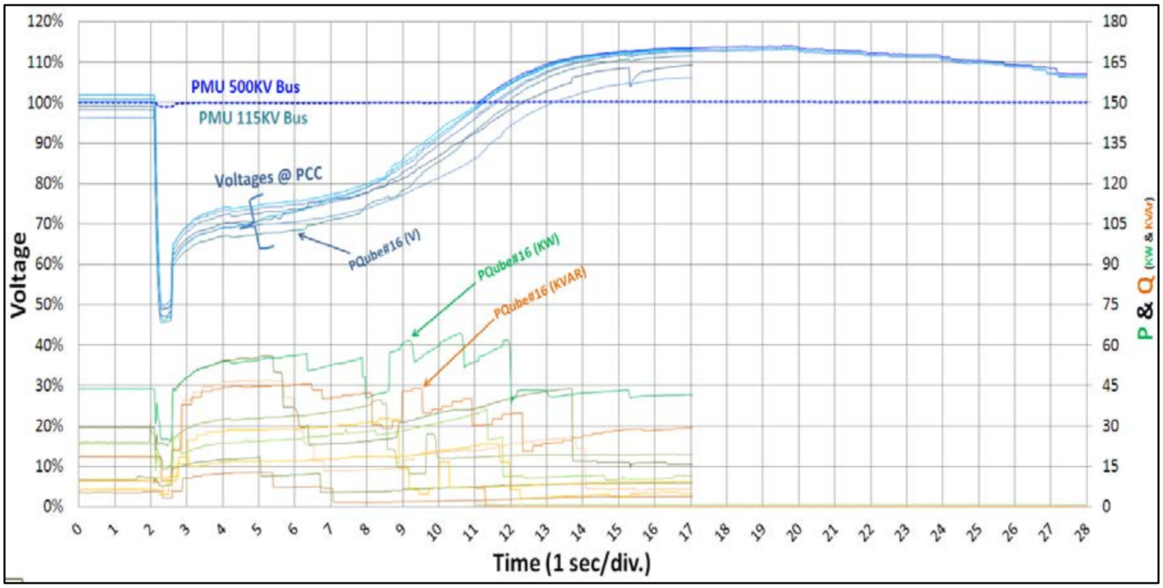

Figure 6.1.1 Event #1 (June 28, 14:44 PDT) RMS Data

In order to assess the events impacts on the distribution circuits, the highest and lowest recovery voltages are plotted in Figure 6.1.2.

The circuit with the highest PCC voltage exhibits these characteristics:

- Real power (P) and reactive power (Q) increased significantly
  - P=1.7X at V=81%, 6.4 seconds after the FIDVR event began
  - Q=3.3X at V=81%, 6.4 seconds after the FIDVR event began
- The FIDVR event lasted approximately 9 seconds
- 48% of load was lost due to RAC’s TOPS 7.5 seconds after the event began
- Circuit experienced overvoltage of 13% above steady-state

The circuit with the lowest PCC recovery voltage exhibited these characteristics:

- P and Q increased significantly

  - P=1.3X at V=69%, in the 5th second of the FIDVR event
  - Q=2.5X at V=69%, in the 5th second of the FIDVR event
- The FIDVR event lasted approximately 10 seconds
- 10% of the load was lost due to RAC's TOPS
- Circuit experienced overvoltage of 12% above steady-state
- P and Q jumps up for less than a second and then lowers some, this could be the starting inrush of the air conditioner compressors

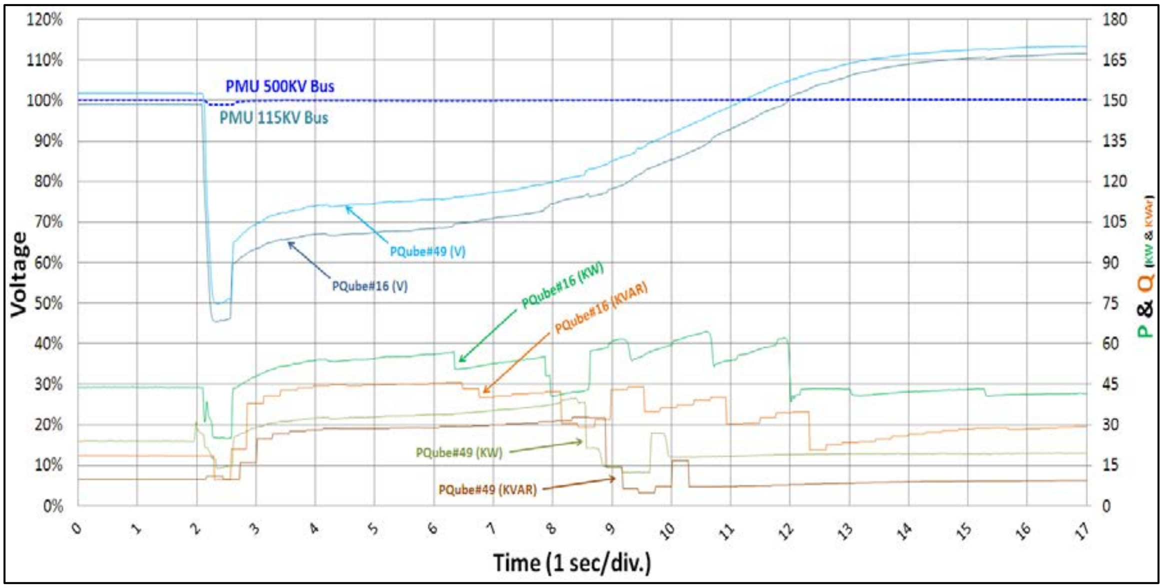

Figure 6.1.2 Event #1 (June 28, 14:44 PDT) RMS Data [two circuits]

The sinusoidal waveform data of the PQ device recorded the lowest voltage circuit Figure 6.1.3 and indicates where the FIDVR event begins. It clearly shows that the stalling voltage point is between 65% and 70% of rated voltage.

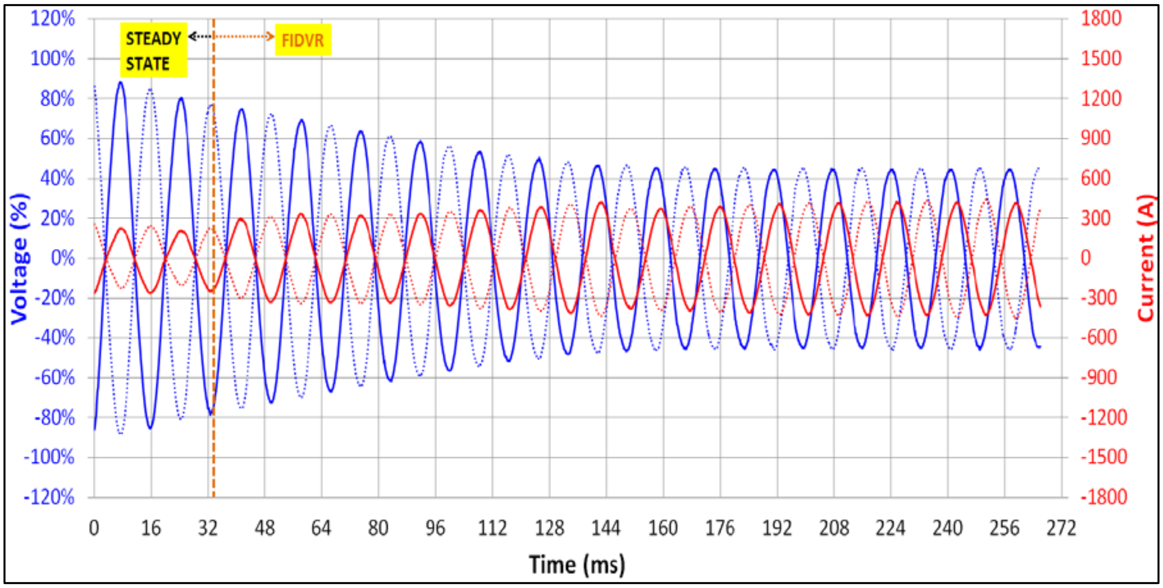

Figure 6.1.3 Event #1 (June 28, 14:44 PDT) Sinusoidal Data

6.2 Event #2 (August 12, 13:09 PDT)

The Grid Control Center (GCC) reported two 115 kV lines relaying in the Valley system when a tarp blew into conductors causing a flashover event. The RMS data for Event #2 shown in Figure 6.2.1 exhibits these characteristics:

- An event was recorded by multiple PQ devices as well as the PMUs at the transmission and subtransmission level
- The first event brought distribution voltages down as low as 85% for just over 1.5 seconds
- The next fault brought the subtransmission (115 kV) voltage down to 91% and PCC voltages (240 V) as low as 45% where RACs stalled
- P and Q increased as such
    - P=1.3X at V=94%, in the 1st second of the FIDVR event
    - Q=1.9X at V=94%, in the 1st second of the FIDVR event
- The FIDVR event lasted approximately 5 seconds before reaching the pre-event voltage
- Loads start disconnecting approximately 3.5 seconds after the FIDVR event is triggered during the second fault
- By the end, 20% of the load was lost after the event due to RAC internal thermal protection switches
- No significant overvoltage was evidenced in this event

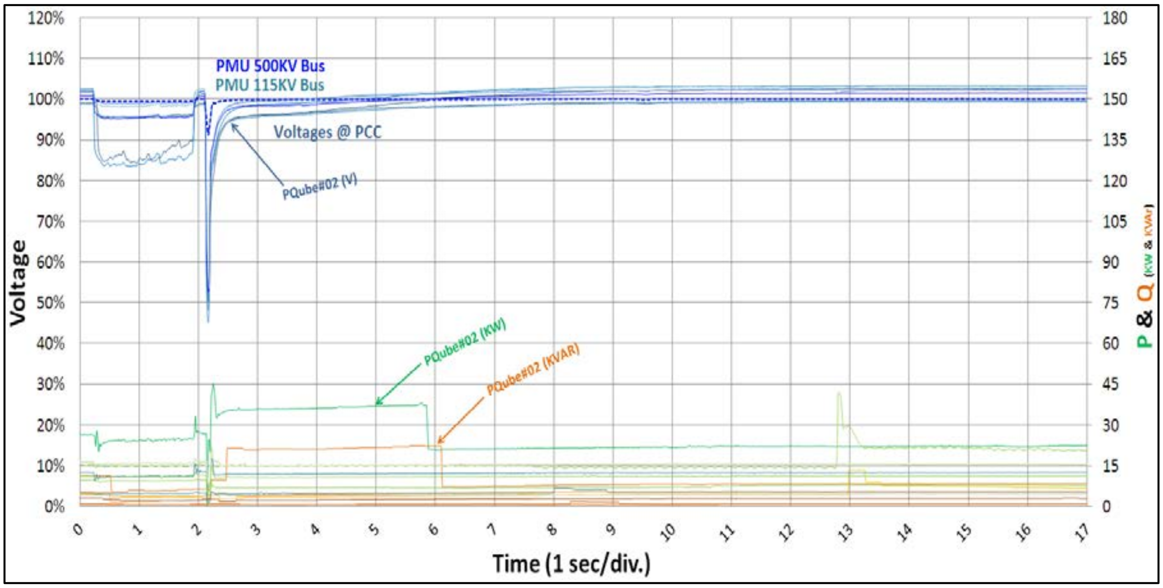

Figure 6.2.1 Event #2 (August 12, 13:09 PDT) RMS Data

The sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6.2.2] indicate that this FIDVR event was initiated at **70 degrees (L2)** on the voltage waveform. This circuit was withdrawing about 180 amps-peak before the event and as high as 410 amps-peak during the event.

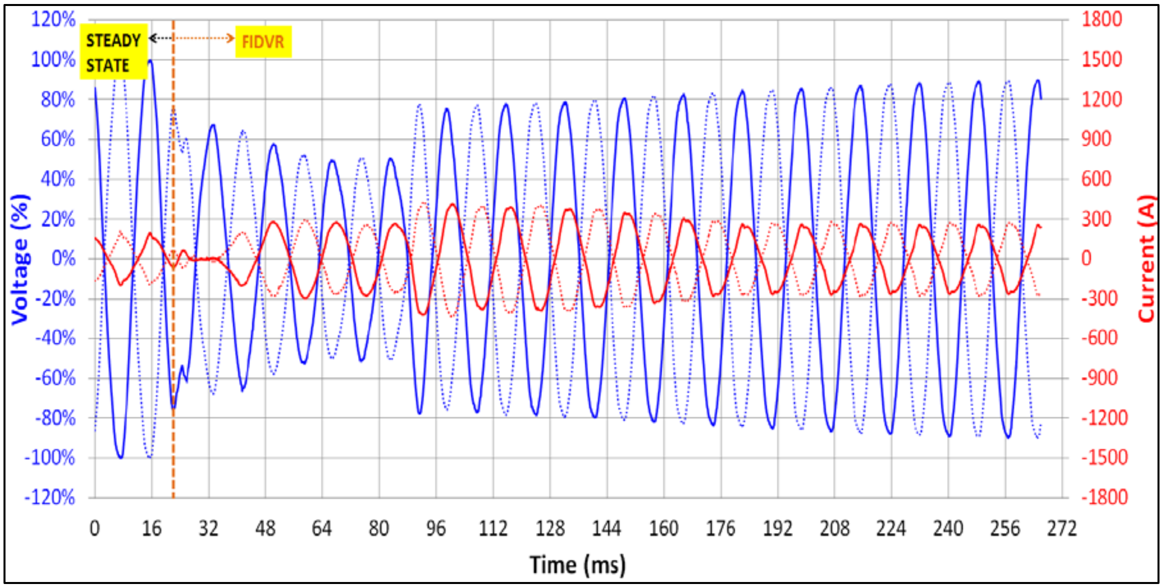

Figure 6.2.2 Event #2 (August 12, 13:09 PDT) Sinusoidal Data

6.3 Event #3 (August 21, 15:13 PDT)

The Grid Control Center (GCC) reported a 115 kV line relaying when a plastic pool blew into an underbuilt 33 kV line and the resultant arc traveled into a 115 kV conductor. Additionally, a 33 kV line and multiple 12 kV lines relayed. A 500 kV capacitor was inserted momentarily. The RMS data for Event #3 shown in Figure 6.3.1 exhibits the following characteristics:

- The event spread through the subtransmission systems as evidenced by PMU data and multiple PQ device recordings
- An initial fault brought the voltage down to 38% and an immediate dip to 60% during recovery where RACs stalled
- After about 1 second, voltage dropped to as low as 42% when additional RACs stalled in several distribution circuits
- PMU signals reveal transmission and subtransmission voltages reducing to 92%.
- The PCC circuits took approximately 11 to 14 seconds for voltage to recover to their respective pre-event voltages
- The loss of the load provoked an overvoltage as high as 19% above steady-state on the distribution circuits and 2% on the subtransmission 115 kV bus

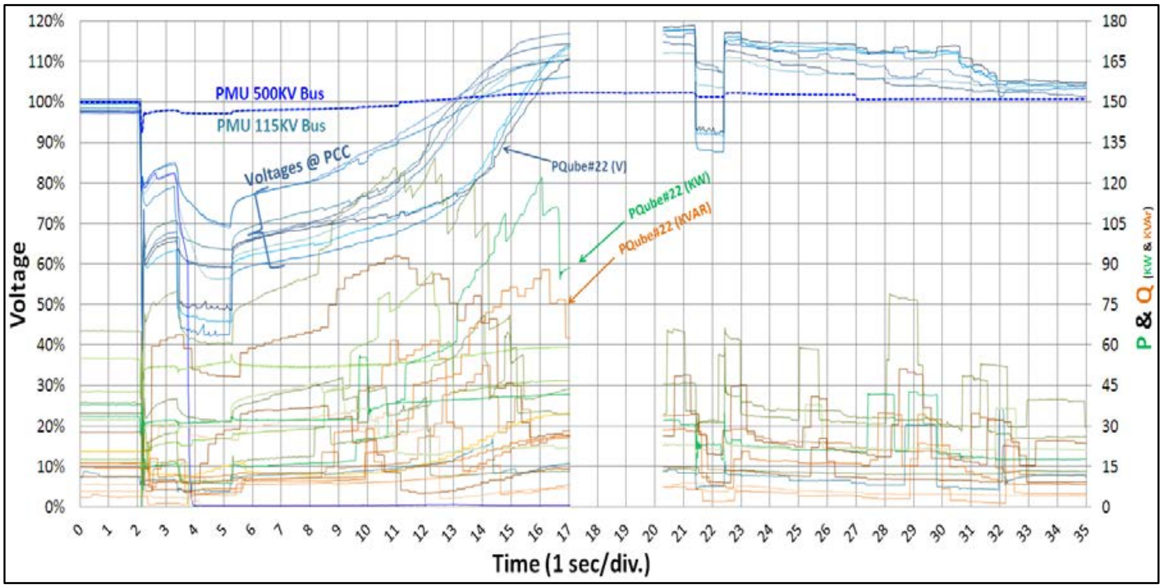

Figure 6.3.1 Event #3 (August 21, 15:13 PDT) RMS Data

In order to assess the events impacts on the distribution circuits, the highest and lowest recovery voltages are plotted in Figure 6.3.2.

The circuit with the highest PCC voltage exhibits these characteristics:

- P and Q increased over time
  - P=1.1X at V=110%, after the under-voltage event recovered
  - Q=1.7X at V=110%, after the under-voltage event recovered
- The FIDVR under-voltage event lasted approximately 11 seconds
- Circuit experienced overvoltage of 10% above steady-state

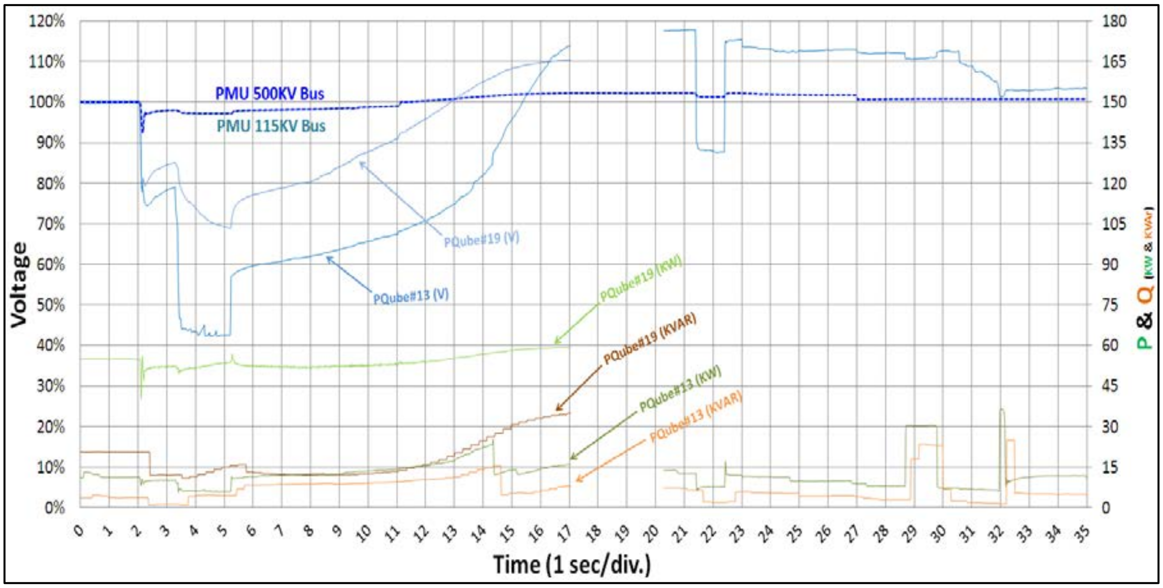

Figure 6.3.2 Event #3 (August 21, 15:13 PDT) RMS Data [two circuits]

The circuit with the lowest PCC voltage recovery had recordings from three different PQ devices. They are plotted in Figure 6.3.3. The circuit exhibited the following characteristics:

- P and Q increased significantly
  - P=3.2X at V=102%, after the under-voltage event recovered
  - Q=5.4X at V=102%, after the under-voltage event recovered
- The FIDVR under-voltage event lasted approximately 13 seconds
- 53% of load was lost due to RAC’s TOPS 33 seconds after the event began
- Circuit experienced overvoltage of 19% above steady-state

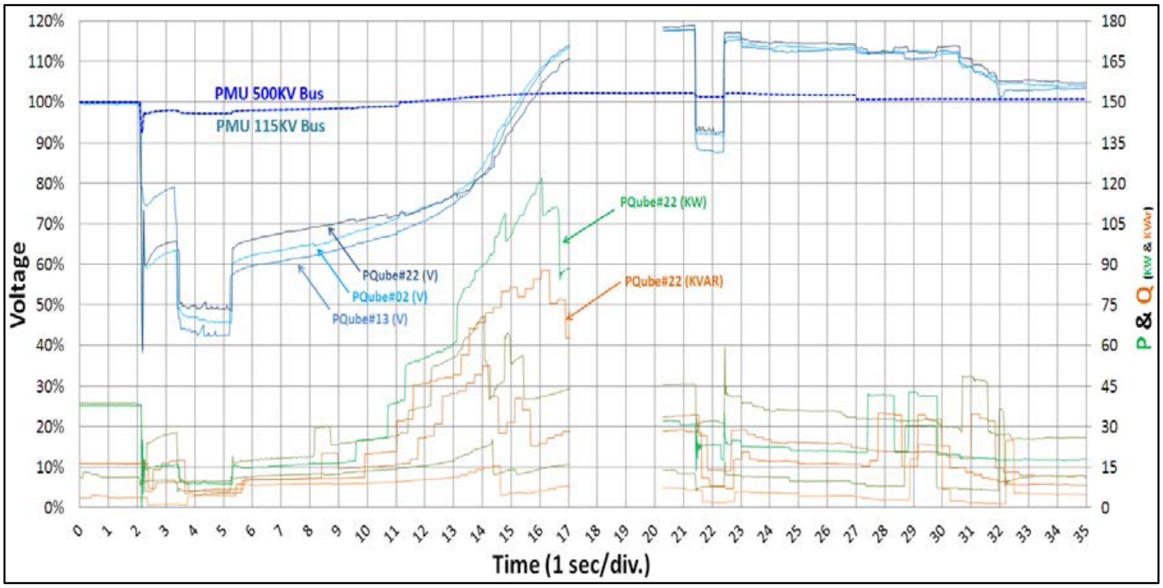

Figure 6.3.3 Event #3 (August 21, 15:13 PDT) RMS Data [one circuit, three phases]

The sinusoidal waveform data of the PQ device that recorded the lowest voltage circuit [Figure 6.3.4] indicate that this FIDVR event was initiated at **<u>70 degrees (L2)</u>** on the voltage waveform. This circuit was withdrawing about 230 amps-peak before the event and as high as 700 amps-peak during the event [not shown in this plot].

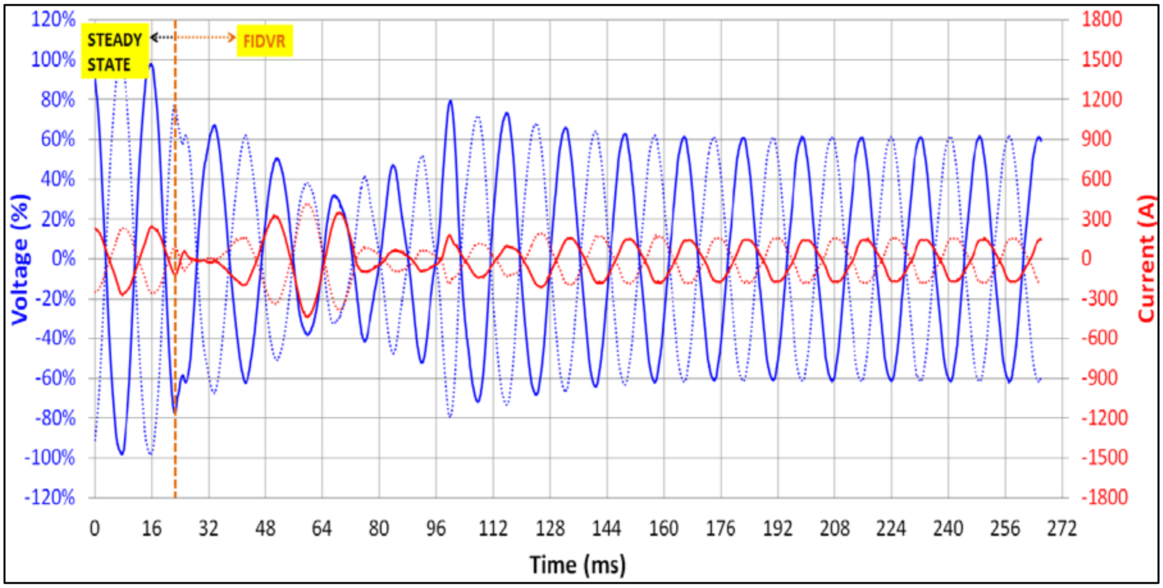

Figure 6.3.4 Event #3 (August 21, 15:13 PDT) Sinusoidal Data

6.4 Event #4 (August 30, 17:02 PDT)

The Grid Control Center (GCC) reported a 115 kV line relaying and reclosing during a storm. The RMS data for Event #3 shown in Figure 6.4.1 exhibits the following characteristics:

- The event spread through the subtransmission systems as evidenced by PMU data and multiple PQ device recordings
- An initial fault brought distribution voltages to as low as 19% of nominal (circuit where stalling occurred had voltage fall to 48% of nominal)
- PMU signals reveal transmission and subtransmission voltages reducing to 85%.
- P and Q increased as such
  - P=2.7X at V=93%, after the 1st second of the FIDVR event
  - Q=4.3X at V=93%, after the 1st second of the FIDVR event
- The PCC circuits took approximately 3 seconds for voltage to recover to their respective pre-event voltages
- Loads start disconnecting approximately 1 second after the FIDVR event is triggered
- By the end, 43% of the load was lost after the event due to RAC internal thermal protection switches
- No significant over-voltage was recorded during this event

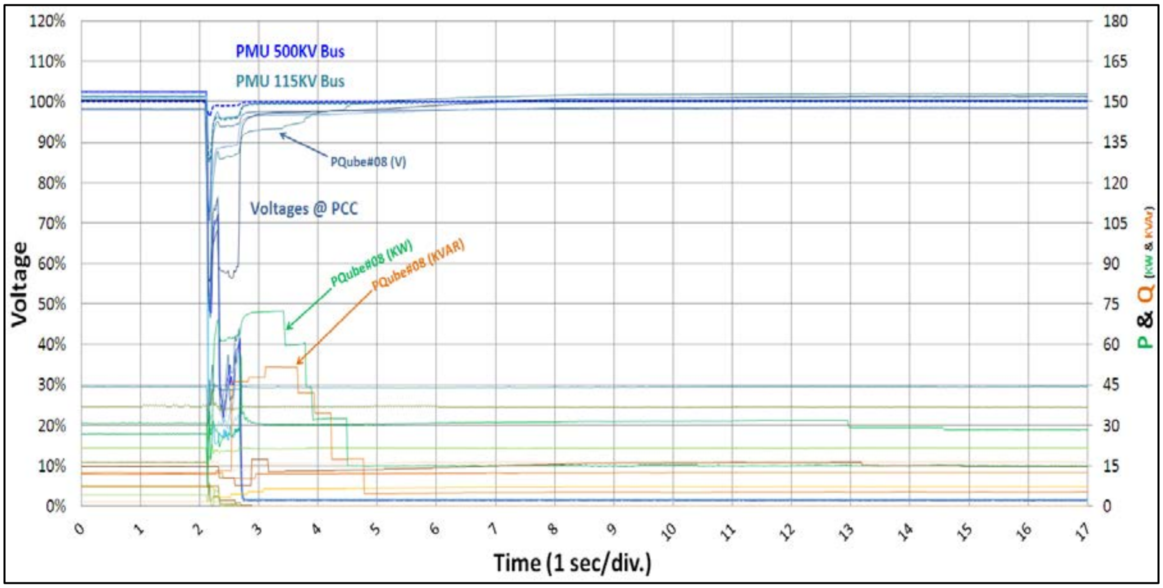

Figure 6.4.1 Event #4 (August 30, 17:02 PDT) RMS Data

One of the PQ recordings is shown in detail in Figure 6.4.2.

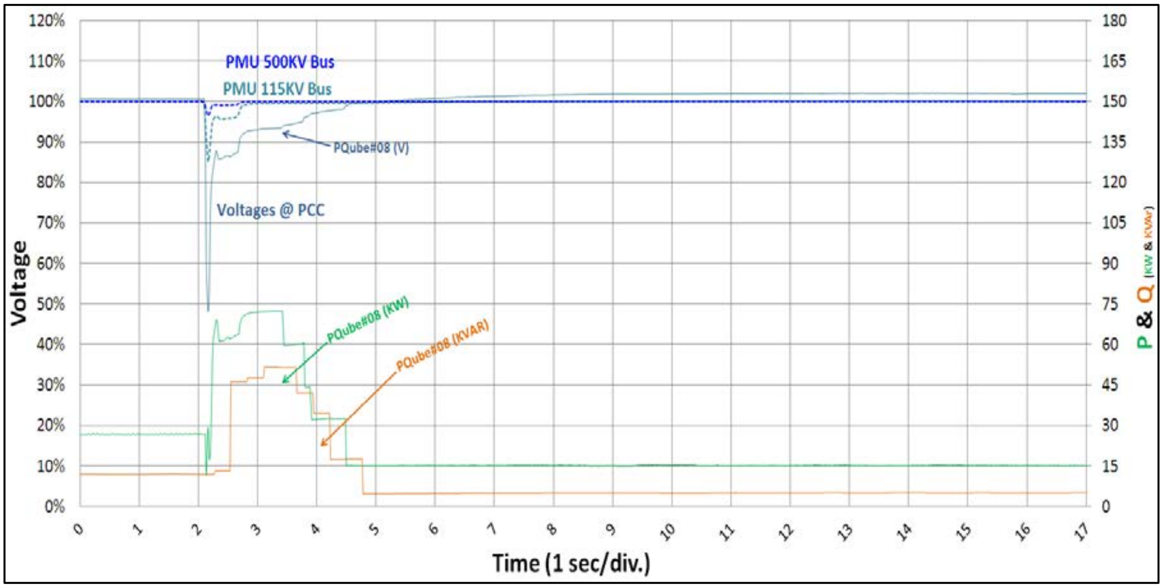

Figure 6.4.2 Event #4 (August 30, 17:02 PDT) RMS Data [one circuit]

One of the circuits disconnected during this event as shown in Figure 6.4.3. This could have been disconnected by the distribution circuit ground relay or overload fuse. The PQ recorders installed on the distribution circuit containing an 8 MW solar PV generation facility (49 and 50) recorded this event.

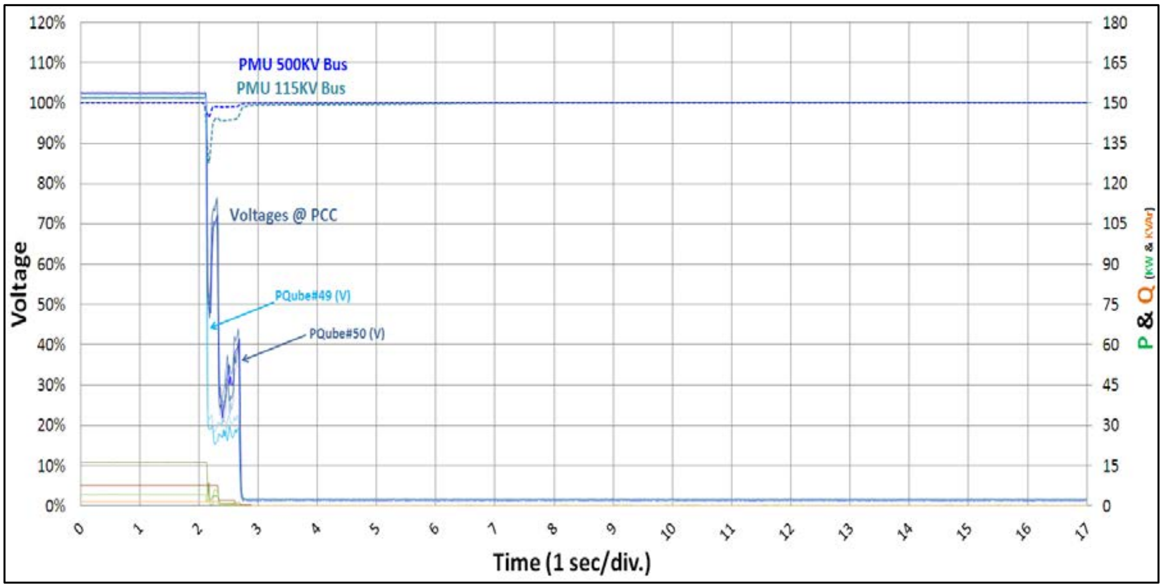

Figure 6.4.3 Event #4 (August 30, 17:02 PDT) RMS Data [one circuit, three phases]

The sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6.4.4] indicate that this FIDVR event was initiated at **50 degrees (L1)** on the voltage waveform. This circuit was withdrawing about 180 amps-peak before the event and as high as 600 amps-peak during the event.

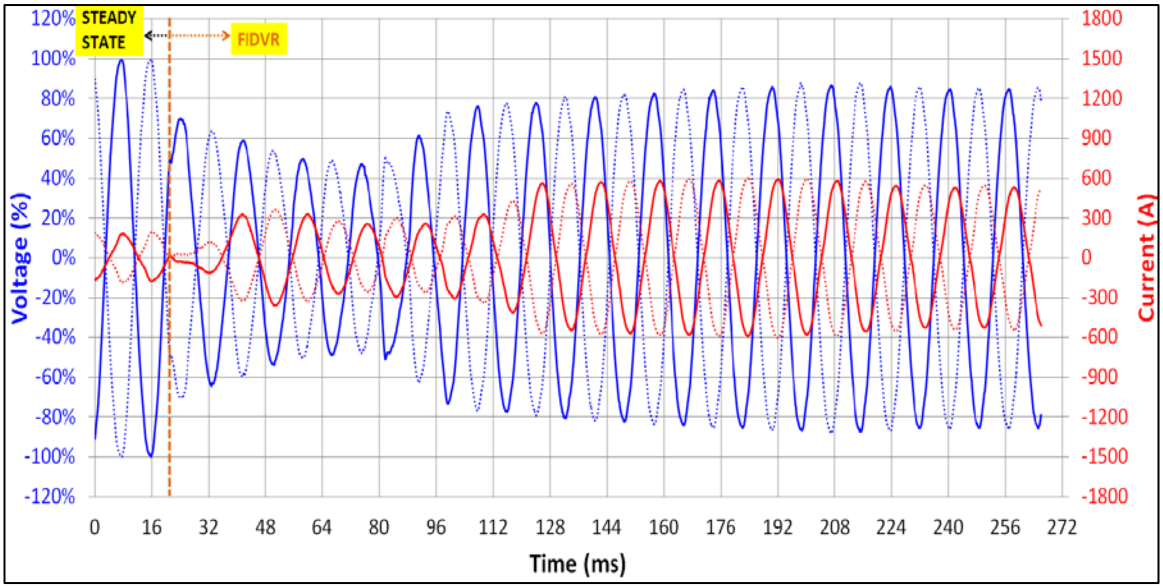

Figure 6.4.4 Event #4 (August 30, 17:02 PDT) Sinusoidal Data

7.0 CONCLUSIONS AND RECOMMENDATIONS

FIDVR events occurrences are mainly due to weather conditions that cause system faults and exhibit some key characteristics that include:

- There are some localized FIDVR events that do not appear in the PMU data (transmission/sub-transmission network), and do not appear to spread
- In 2013 the worst event occurred in Section C Valley 115 kV bus sub-transmission network that covers the west side of Valley Substation coverage
- Sinusoidal data suggests that:
    - RAC units 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 suggest that the current leads the voltage, but thereafter it goes to pre-event conditions with current lagging voltage
- Additional RAC units can stall in the middle of a FIDVR event, suggesting a cascading effect

Another important observation revealed while analyzing the FIDVR event data is that all the per-unitized voltages in the network (transmission, sub-transmission, and customer PCC) are the same at steady-state; however, their values vary significantly immediately after the FIDVR event begin indicating differences in RAC load and system impedance during the FIDVR events. This is relevant to engineers trying to determine the proper load composition for their system studies. Use of the WECC's composite load model requires the modeler to set the parameter for penetration of RAC load lower than what is actually connected to replicate a system event during validation studies. 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.

Capturing this kind of data using a PQ monitoring device requires voltage and current levels to be set properly. For this study voltage levels were set low enough to only capture FIDVR events and not normal voltage sags. Overvoltage settings were adjusted high enough to only capture significant events and not more common swells.

A final observation is that areas with a high RAC penetration tend to be experiencing rapid increases in solar photovoltaic (PV) generation, which could significantly worsen FIDVR effects. This is because present solar PV standards do not allow voltage ride-through (VRT). Without both low and high voltage ride-through for solar PV systems, this type of local generation will most likely disconnect during these events. This could negatively impact transmission networks in areas with growing amounts of solar PV generation. If PV inverters were equipped with volt/var schedule options, as German inverters are, the PV generation could become a key to reliability instead of having a negative impact.

Table 7.0.1 has the summary where all the faults begin in the voltage waveform. The faults starting point may not have been a contributor to the FIDVR events.

	t_{FAULT}		
Event	**Degrees**	**Reading at Line**	**Comments**
1	----		PQ recorder failed to record the beginning of the fault
2	250	L1	
3	250	L1	
4	50	L1	

Table 7.0.1 Fault Initiation Time in the voltage Waveform

8.0 ADDITIONAL VOLTAGE EVENTS

The following voltage events were also captured along with FIDVR events during the summer of 2013. All voltage values (%) have been measured at the secondary side of the transformer with a base of 240 V, line-to-line.

8.1 Event #1 (July 02, 05:24 PDT)

The RMS data for the following event shown in Figure 8.1.1 was captured from PQ 18 and exhibited these characteristics:

- The event appears to be localized because it was only captured by a PQ device at single location
- Voltage periodically dips and recovers. During one of these dips, the voltage displays oscillating behavior for approximately 15 cycles
- The voltage deviates as far as 23% below nominal voltage
- Real power at the circuit location appears to be oscillating with voltage, may have been an arcing fault

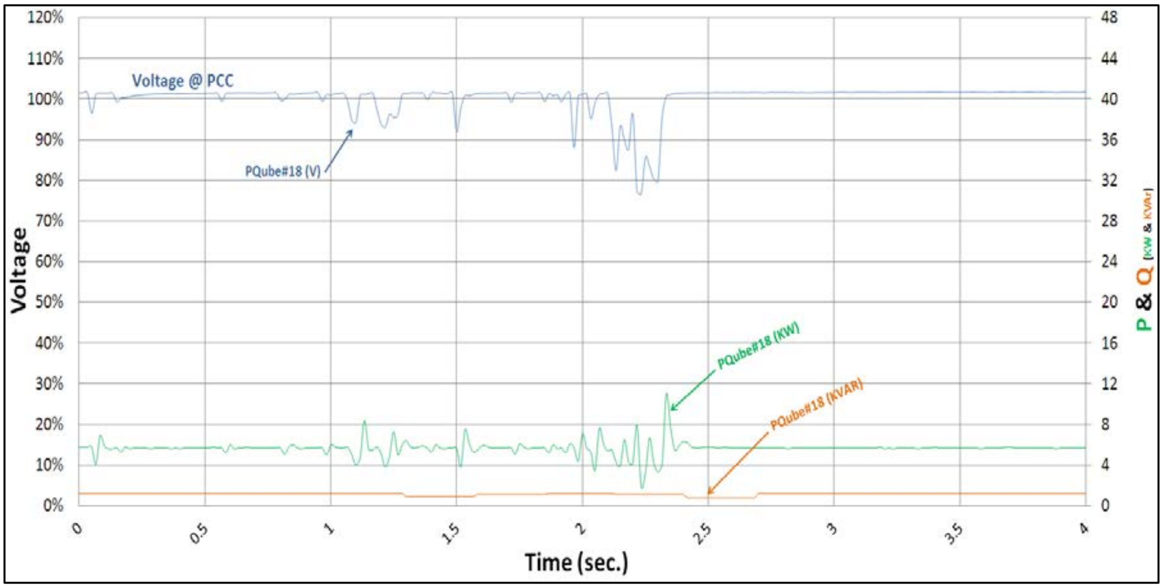

Figure 8.1.1 Event #1 (July 02, 05:24 PDT) RMS Data [PQ 18]

8.2 Event #2 (July 2, 09:45 PDT)

This event was captured from the same device as the previous event (PQ 18) and occurred on the same day. The RMS data for this event shown in Figure 8.2.1 exhibited the following characteristics:

- As with the previous event, this too appears to be localized because it was only captured by a PQ device at single location
- Voltage dips and begins to display oscillating behavior for approximately 23 cycles.
- Voltage deviates as far as 27% below nominal voltage
- Real power at the circuit location appears to be oscillating with voltage

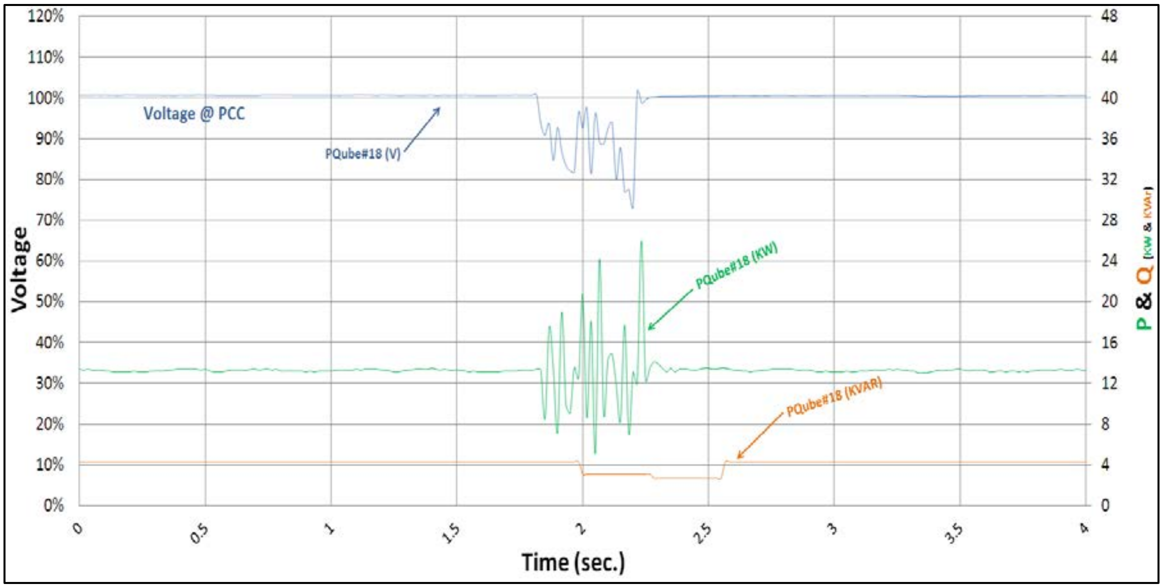

Figure 8.2.1 Event #2 (July 02, 09:45 PDT) RMS Data [PQ 18]

8.3 Event #3 (July 11, 18:07 PDT)

The following event was captured from PQ devices 13 and 20 located on phase C in the "Section C&D bus" (Eastern system). The RMS data for this event shown in Figure 8.3.1 exhibited the following characteristics:

- The voltage transient appears to be the result of a localized FIDVR event on an adjacent circuit
- Voltage drops to 75% of nominal for PQ 20 and below 10% for PQ 13
- One of the PCC circuits took approximately 4 seconds for voltage to recover to its respective pre-event voltage value
- Although the under voltage transient was extremely low, it did not provoke A/C stalling on either of the monitoring locations for PQ 13 and 20

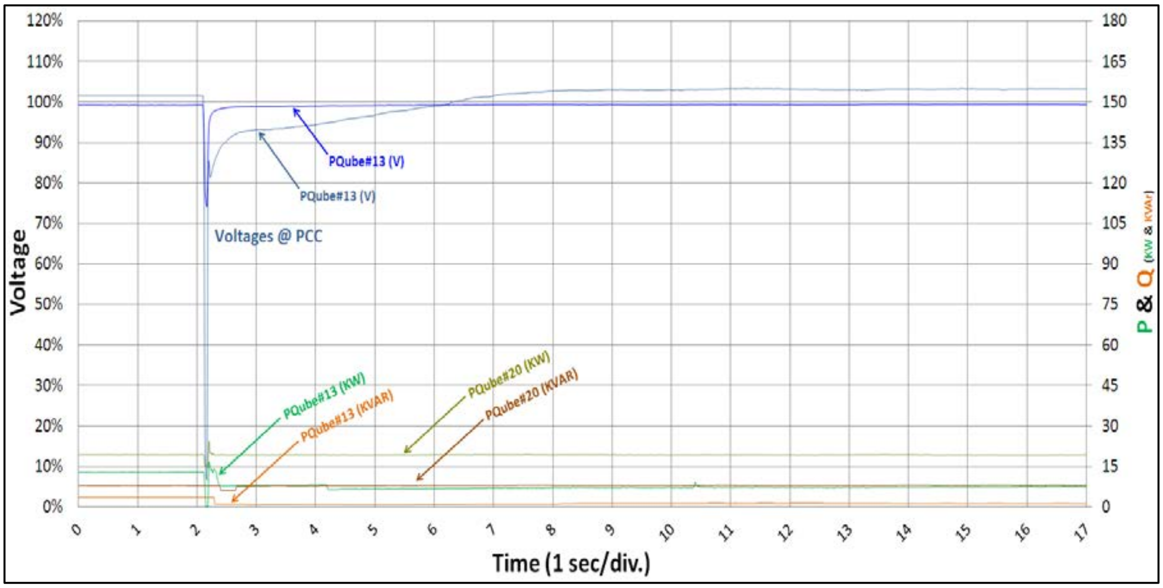

Figure 8.3.1 Event #3 (July 11, 18:07 PDT) RMS Data [PQ 13,20]

8.4 Event #4 (August 30, 06:47 PDT)

The following event was captured from PQ devices 1, 5, 6, 7, 8, 15, 16, 49, and 50 located in the “Section A&B bus” (Western system). According to the Grid Control Center (GCC), the event is the result of a 115 kV line relaying due to a vehicle hitting a pole. The RMS data for this event shown in Figure 8.4.1 exhibited the following characteristics:

- Voltage drops to as low as 54% of nominal as observed by PQ 1
- The PCC circuits took approximately 1.2 seconds for voltages to recover to their respective pre-event voltage values
- Although this undervoltage transient may have stalled A/C unit(s) on a single circuit, it did not provoke a FIDVR event
- Stalled load(s) disconnect approximately 3 seconds after the transient event
- A/C load was likely low during the time of the event (early morning)

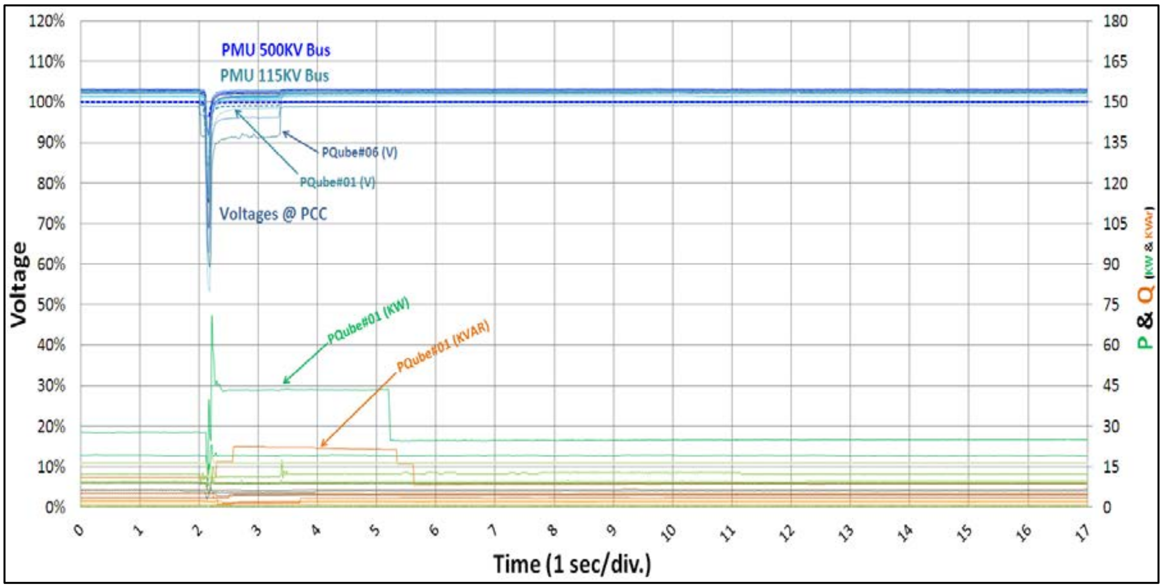

Figure 8.4.1 Event #4 (August 30, 06:47 PDT) RMS Data [PQ 1,5,6,7,8,15,16,49,50]

8.5 Event #5 (August 30, 17:09 PDT)

The following event was captured from PQ devices 11, 18, 49, and 50 located in the "Section A&B bus" (Western system). According to the Grid Control Center (GCC), the event is the result of a 115 kV line relaying and reclosing during a storm. The RMS data for this event shown in Figure 8.5.1 exhibited the following characteristics:

- Voltage drops to as low as 45% of nominal as observed by PQ 18
- The PCC voltage took approximately 4 seconds to recover to its respective pre-event voltage value
- Although this undervoltage transient may have stalled A/C unit(s) on a single circuit, it did not provoke a FIDVR event
- Stalled load(s) disconnect within one second following the transient event
- This event occurred shortly after a captured FIDVR event (at 17:02 PDT) and after the voltages at PQ 49 and 50 had been interrupted

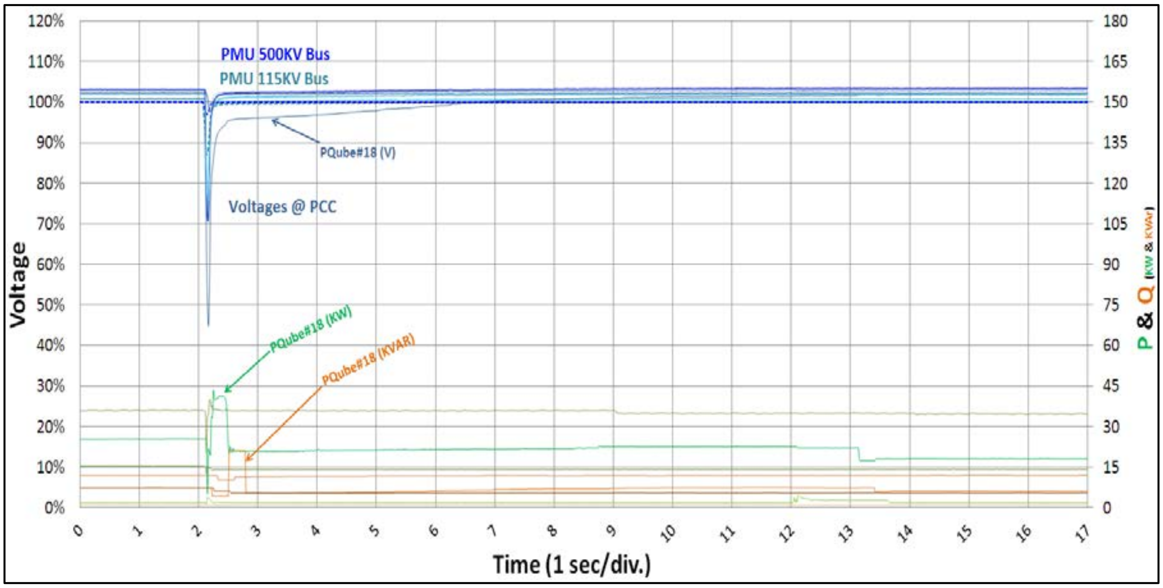

Figure 8.5.1 Event #5 (August 30, 17:09 PDT) RMS Data [PQ 11,18,49,50]

8.6 Event #6 (September 5, 15:03 PDT)

The following event was captured from PQ devices 1 and 5 located in the “Section A&B bus” (Western system). The RMS data for this event shown in Figure 8.6.1 exhibited the following characteristics:

- The voltage transient appears to be the result of a FIDVR event on an adjacent circuit
- Voltage drops to as low as 80% of nominal on the observed PCC circuits
- The PCC voltages captured took approximately 7 seconds for voltage to recover to it pre-event value
- Although an undervoltage transient occurred, it was not low enough to provoke A/C stalling on either of the monitoring locations for PQ 1 and 5

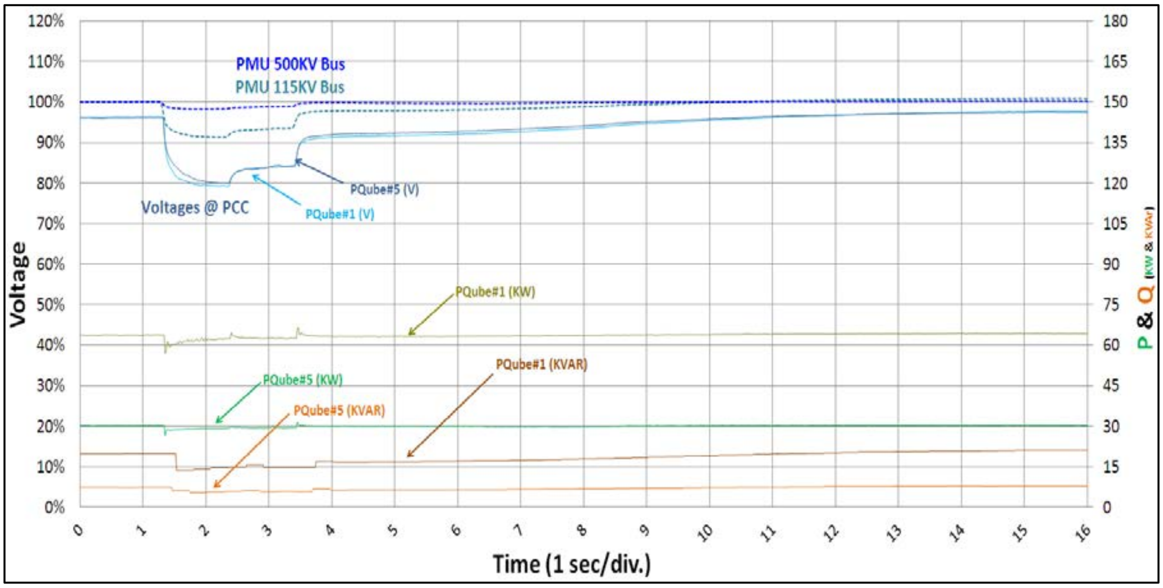

Figure 8.6.1 Event #6 (September 5, 15:03 PDT) RMS Data [PQ 1,5]

8.7 Event #7 (September 14, 10:56 PDT)

The following event was captured from PQ device 11 located in the “Section A&B bus” (Western system). The RMS data for this event shown in Figure 8.7.1 exhibited the following characteristics:

- The initial fault brought the voltage momentarily down to 77% of nominal and again a couple more time to a lesser degree
- A transient event then dropped voltage to as low as 29% of nominal
- The PCC circuit took approximately 4 seconds for voltages to recover after the last fault
- Although this undervoltage transient may have stalled A/C unit(s) on a single circuit, it did not provoke a FIDVR event
- Stalled load(s) disconnect within 1 second after the last undervoltage transient
- A/C load was likely low during the time of the event (before noon)

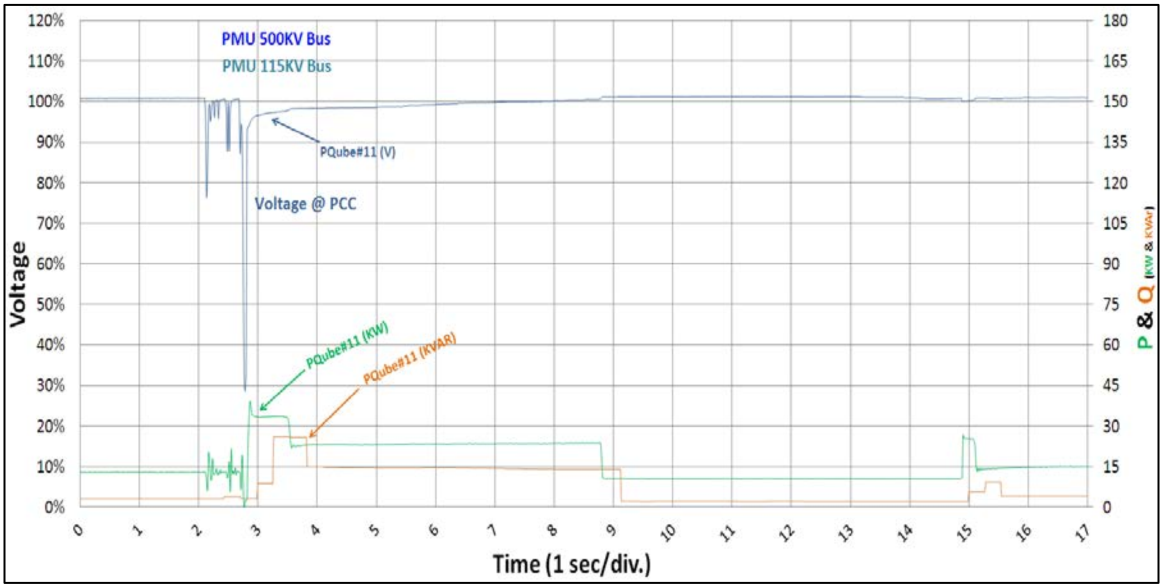

Figure 8.7.1 Event #7 (September 14, 10:56 PDT) RMS Data [PQ 11]

8.8 Event #8 (September 14, 11:22 PDT)

The following event was captured from PQ device 11 located in the “Section A&B bus” (Western system). The RMS data for this event shown in Figure 8.8.1 exhibited the following characteristics:

- Voltage drops to as low as 28% of nominal as observed by PQ 11
- The PCC circuit took approximately 4 seconds for voltages to recover to nominal voltage
- Although this undervoltage transient may have stalled A/C unit(s) on a single circuit, it did not provoke the response of a FIDVR event
- Stalled load(s) begin disconnecting within 1 second after the transient event and are tripped off completely after another 4 seconds
- A/C load was likely relatively low during the time of the event (before noon)

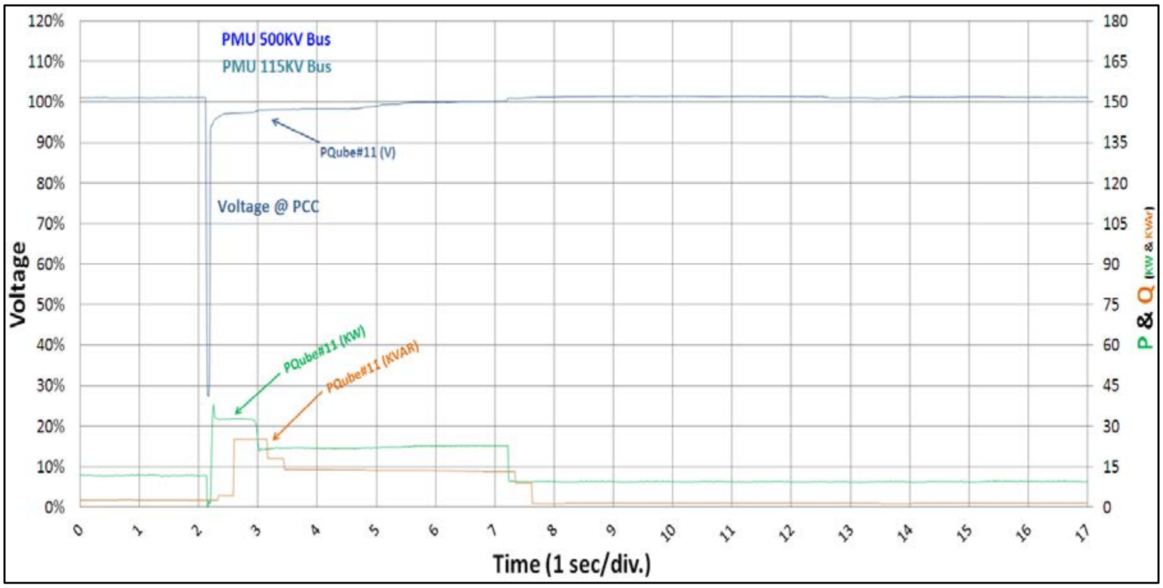

Figure 8.8.1 Event #8 (September 14, 11:22 PDT) RMS Data [PQ 11]