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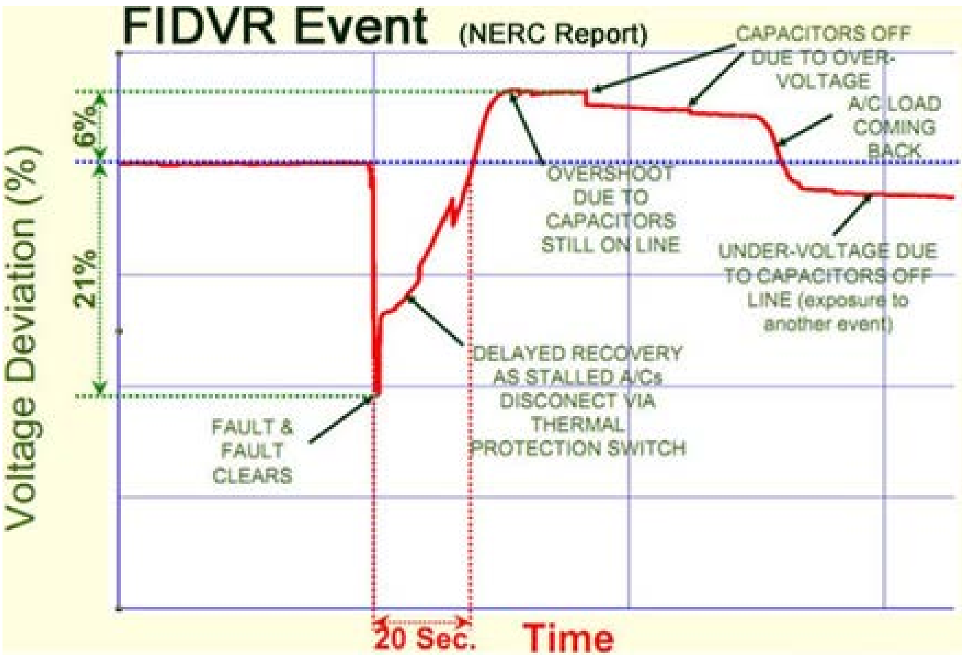
2012 FIDVR Events Analysis
Valley Distribution Circuits



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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.

To improve grid reliability, SCE is investing billions of dollars to replace and upgrade its electric system infrastructure, which includes more than 100,000 miles of circuits and 1.5 million poles.

Advanced Technology is the organization in SCE's Transmission and Distribution business unit and Engineering & Technical Services (E&TS) division 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.

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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 authors acknowledge the additional support of the U.S. Department of Energy through the Lawrence Berkeley National Laboratory who provided the distribution monitoring devices used to capture these system events and participated in the analysis contained in this report. Furthermore, all the authors are grateful to Rex Klinkenborg, supervisor at SCE's Valley Sector distribution substation and field troubleman David Meekhof for providing continuous support in the installation of these devices.

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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 1-1. It 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.

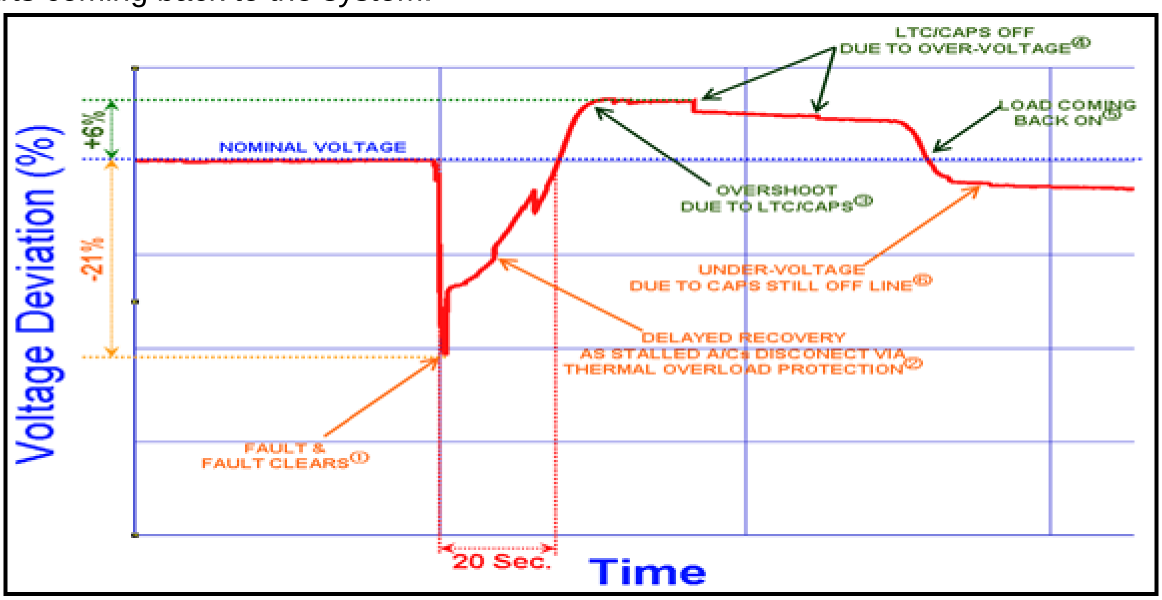

Figure 1-1 FIDVR Anatomy

In most cases, these events are localized and do not cascade or spread throughout the transmission system to cause outages. There is concern that should 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 investigating FIDVR events and testing performed by its members on 27 RAC units during voltage and frequency deviations 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%
- A small quantity of scroll RAC tend to restart faster after they stalled
- 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.

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 17 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.

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 DEVICE SETUP

Advanced Technology's DER laboratory put together a flexible power quality device to be installed in the field, specifically distribution transformers, as shown in Figure 3-1. The power quality recording devices (PQubes) 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 32 samples/cycle (for approximately 64 cycles)

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 PQube setup has the following components:

1. PQube module: records data and provides the voltage inputs
2. Current module: provides current inputs
3. Power supply: transforms the input voltage down to 24 VAC to power the PQube
4. Circuit breaker: protects the PQube
5. Current transformers (CTs): transforms the currents to 0.333V at full scale.
6. Voltage leads with banana plug connectors: provides flexibility for voltage measurements in a field installation
7. Din rail
8. Enclosure

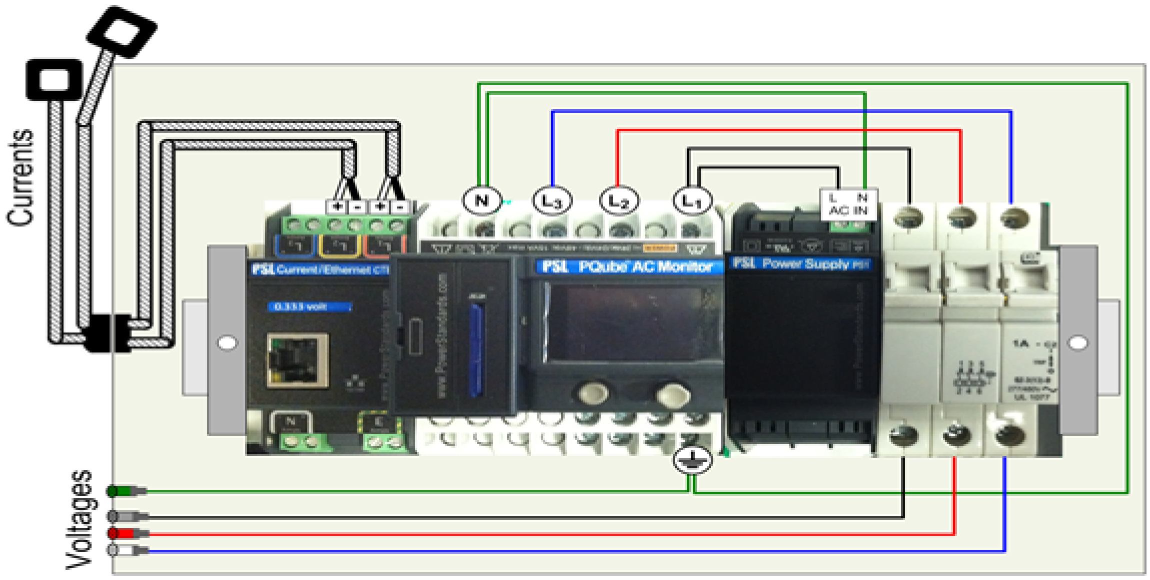

Figure 3-1 SCE's PQ Device Setup

4.0 FIELD INSTALLATION

At the beginning of the study, the PQ devices 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 PQubes 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 4-1, illustrates the transformer's primary side 6.9 kV phase-to-ground and secondary side 240 V line-to-line connections.

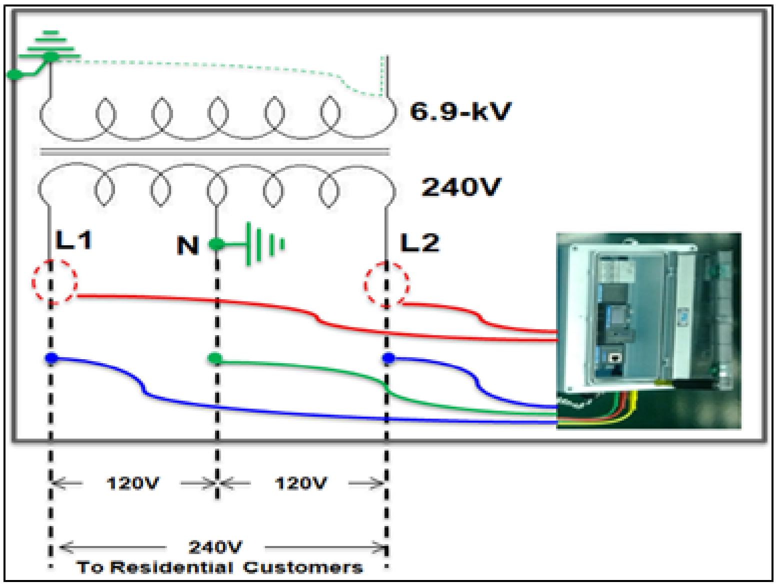

Figure 4-1 PQube Pad Mount Transformer Installation Diagram

One of the 22 actual installations used for the study is shown in Figure 4-2. 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.

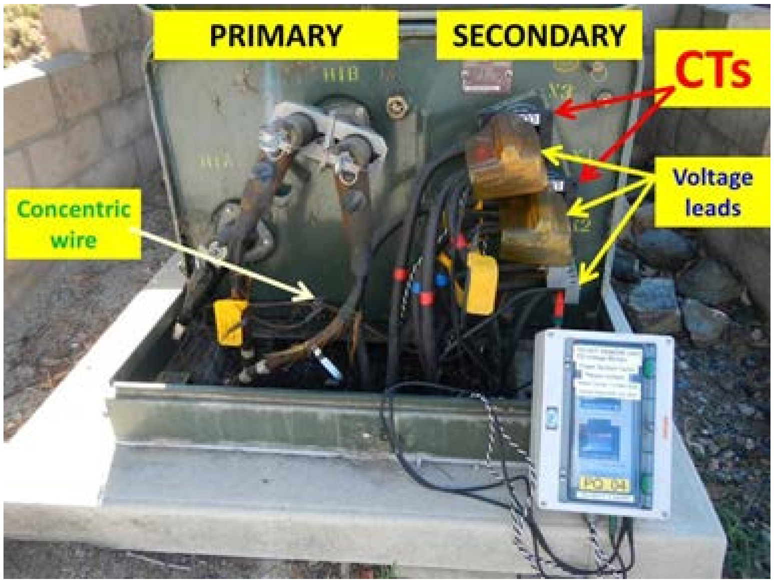

Figure 4-2 PQ Monitor Field Intallation in a Pad Mount Transformer

5.0 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:

- Transmission system contains two 115 kV busses, Section A&B and Section C&D.
- 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 17 of Valley's 24 meshed sub-transmission (115 kV) systems as shown in Figure 5-1. 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.

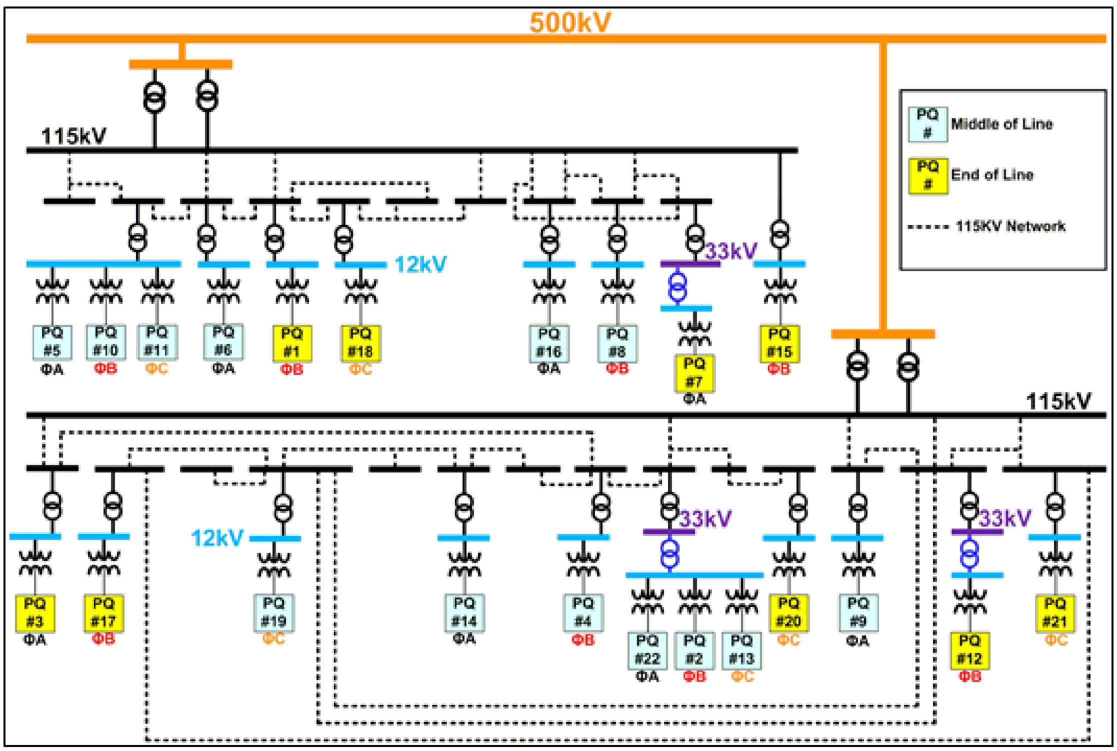

Figure 5-1 Valley PQubes Locations Diagram

6.0 SUMMER 2012 EVENT ANALYSIS

The events analyzed for this study were recorded throughout the summer of 2012. 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 (July 10, 20:08 PDT)

The RMS data for Event #1 shown in Figure 6-1 exhibit these characteristics:

- The event was localized to the distribution circuit because no other PQ device or PMUs recorded the event.
- Six lightning strikes caused multiple distribution faults as seen in the recordings.
- The first fault did not stall RACs because circuit voltage was above 90% of nominal; this lighting strike may have been far from this distribution circuit.
- The second fault reduced voltage to 60% causing some loads to stall.
- Real power (P) and reactive power (Q) increased significantly
    - P=2.78X (times the steady-state value) at V=90%,3 seconds into the FIDVR event
    - Q=8.64X (times the steady-state value) at V=90%,3 seconds into the FIDVR event
- The FIDVR event lasted approximately 9 seconds.
- The stair-shaped profile for real power indicates that several loads disconnected approximately 6 seconds after the FIDVR event was triggered (could be due to TOPS opening and tripping off RAC units).
- 50% of the load disconnected itself by the end of the event.
- No overvoltage was recorded for this event.

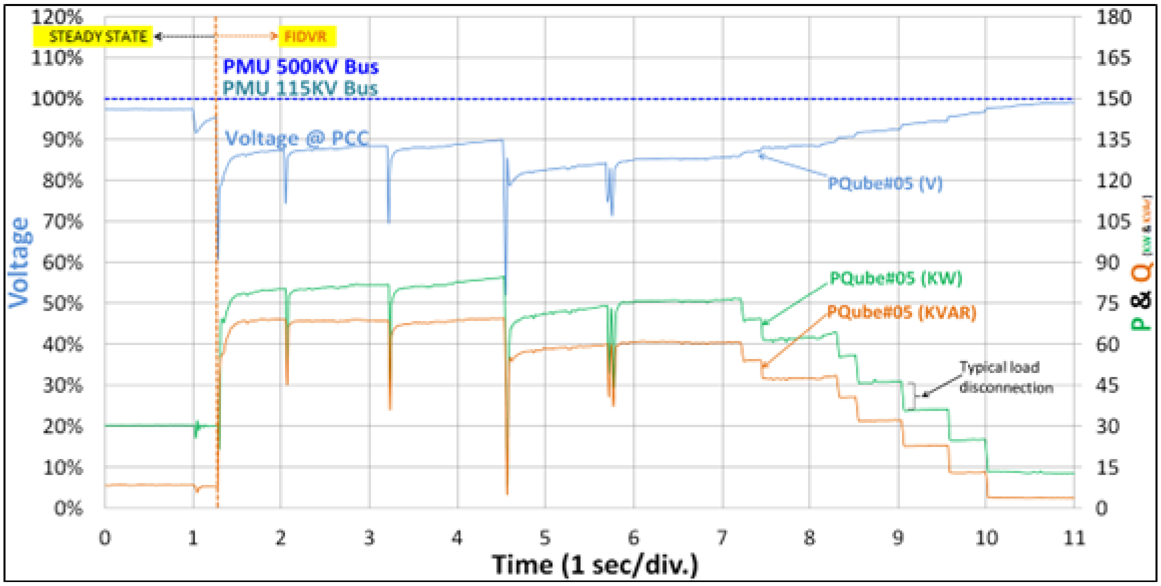

Figure 6-1 Event #1 (July 10, 20:08 PDT) RMS Data

According to this event's sinusoidal waveform data [Figure 6-2], the FIDVR event was detected at **50 degrees** after the zero crossing of the voltage waveform. The RAC stalled in about 1 cycle, providing evidence that RAC take less than 3 cycles to stall.

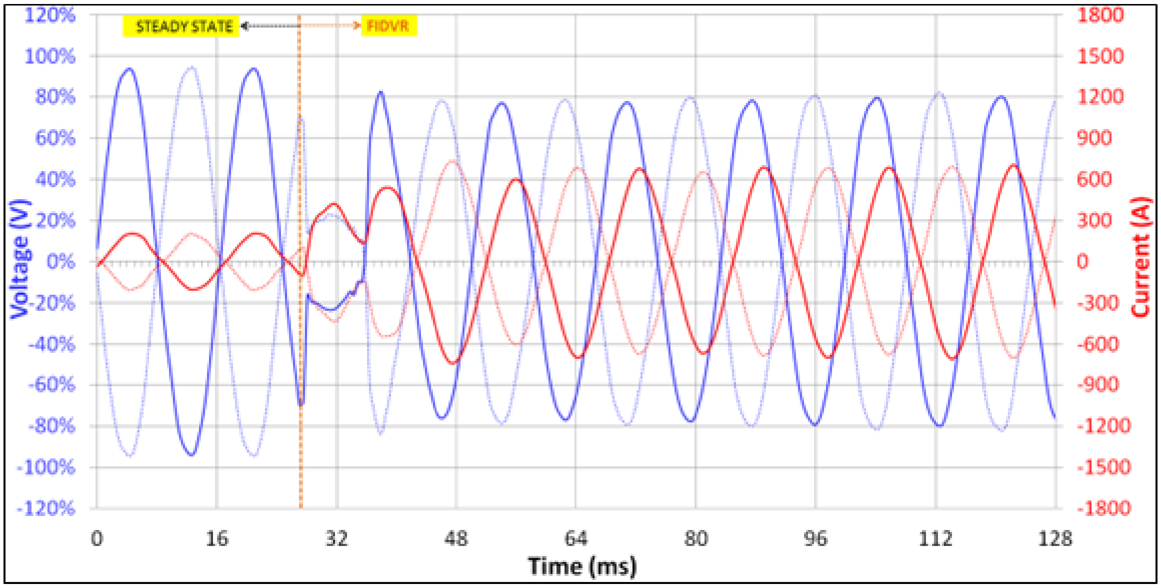

Figure 6-2 Event #1 (July 10, 20:08 PDT) Sinusoidal Data

6.2 Event #2 (August 6, 14:07 PDT)

The RMS data for Event #2 shown in Figure 6-3 exhibit these characteristics:

- The event may have spread to various distribution or subtransmission systems since it was detected by the PMU at the 115 kV bus.
- Two low voltages are observed. These low voltages were recorded during a storm day and were most likely caused by lightning.
- The first low voltage did not stall RACs because the circuit voltage was above 90% of nominal.
- The second fault brought the voltage down to 65% causing RAC to stall.
- P and Q increased significantly
    - o P=2.0X at V=82%,0.5 seconds into the FIDVR event
    - o Q=5.50X at V=82%,0.5 seconds into the FIDVR event
- The FIDVR event lasted approximately 8 seconds
- Loads start tripping right after the start of FIDVR; it appears that at least 5 loads tripped off during this event.
- 40% of the load was lost by the end of the event due to RACs internal thermal protection switches.
- No overvoltage was recorded for this event.

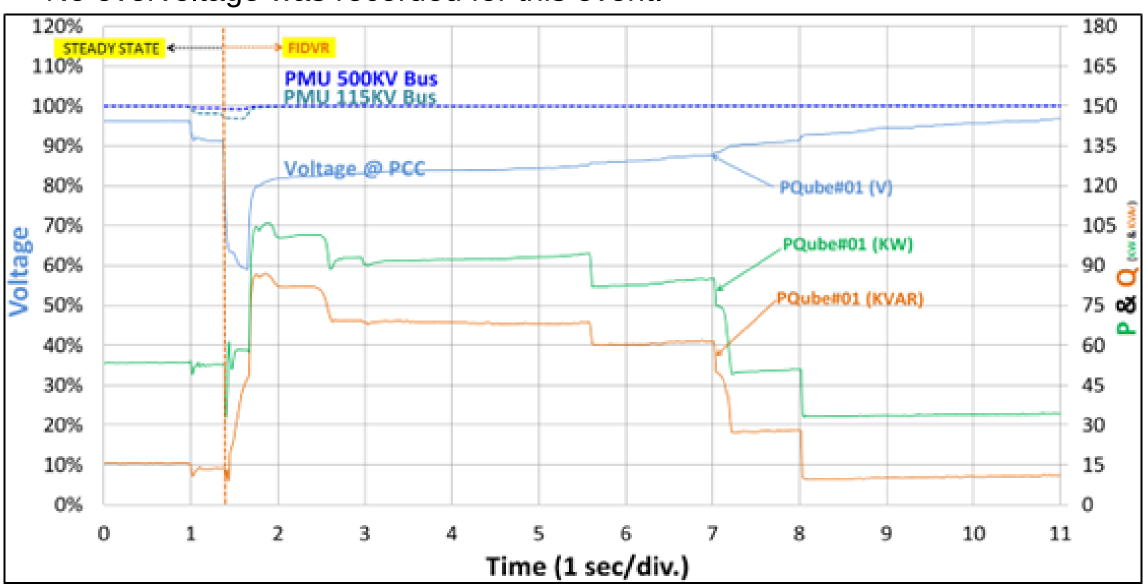

Figure 6-3 Event #2 (August 6, 14:07 PDT) RMS Data

According to this event's sinusoidal waveform data [Figure 6-4 and Figure 6-5], the FIDVR event was initiated with a low voltage that started at **150 degrees** into the voltage waveform. The waveform current increased from 370 to 1,000 amps peak.

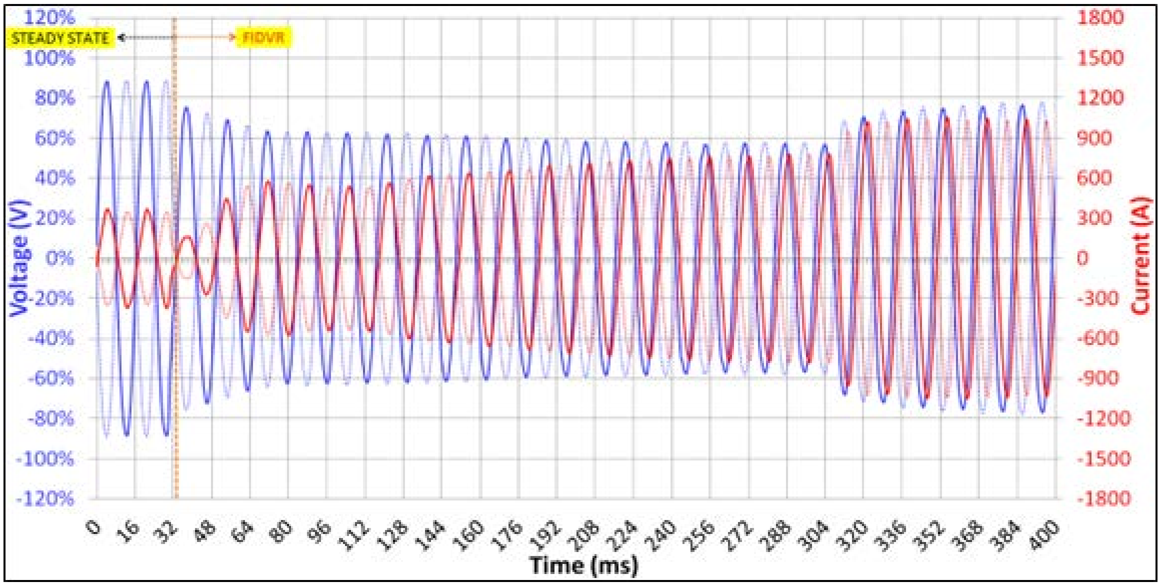

Figure 6-4 Event #2 (August 6, 14:07 PDT) Sinusoidal Data

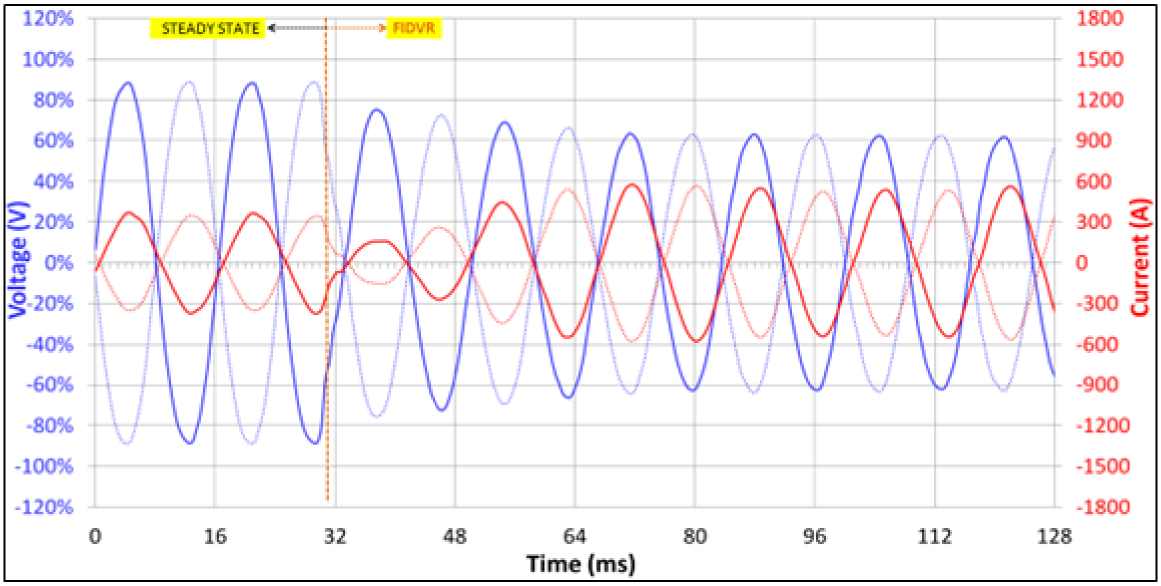

Figure 6-5 Event #2 (August 6, 14:07 PDT) Sinusoidal Data [zoomed in]

6.3 Event #3 (August 10, 14:14 PDT)

The RMS data for Event #3 shown in Figure 6-6 exhibit these characteristics:

- A fault caused by lightning strikes appeared only in the distribution circuit, but almost completely washed out in the PMU data.
- The fault brought the voltage down to 40% where RACs stalled.
- At least two RAC units stalled in a cascading effect (as shown in the 2 and 5 second marks of the Figure 6-6).
- P and Q increased significantly
  - P=1.8X at V=84%, 8 seconds after the FIDVR event starts
  - Q=4X at V=84%, 8 seconds after the FIDVR event starts
- The FIDVR event lasted approximately 12 seconds before reaching pre-event voltage.
- Loads start disconnecting approximately 1 second after the FIDVR event is triggered. At least 5 big residential loads tripped during the course of the event.
- By the end, 40% of the load was lost due to RAC internal thermal protection switches.
- No overvoltage was evidenced in this event.

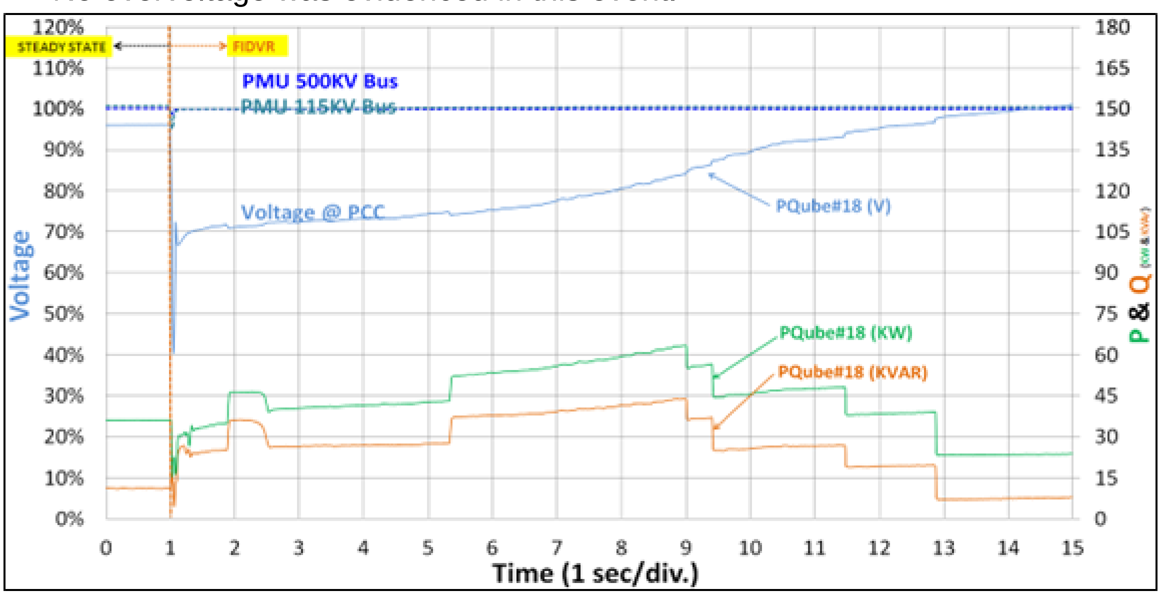

Figure 6-6 Event #3 (August 10, 14:14 PDT) RMS Data

According to this event's sinusoidal waveform data [Figure 6-7], the FIDVR event was initiated with a low voltage that started at **60 degrees** into the voltage waveform.

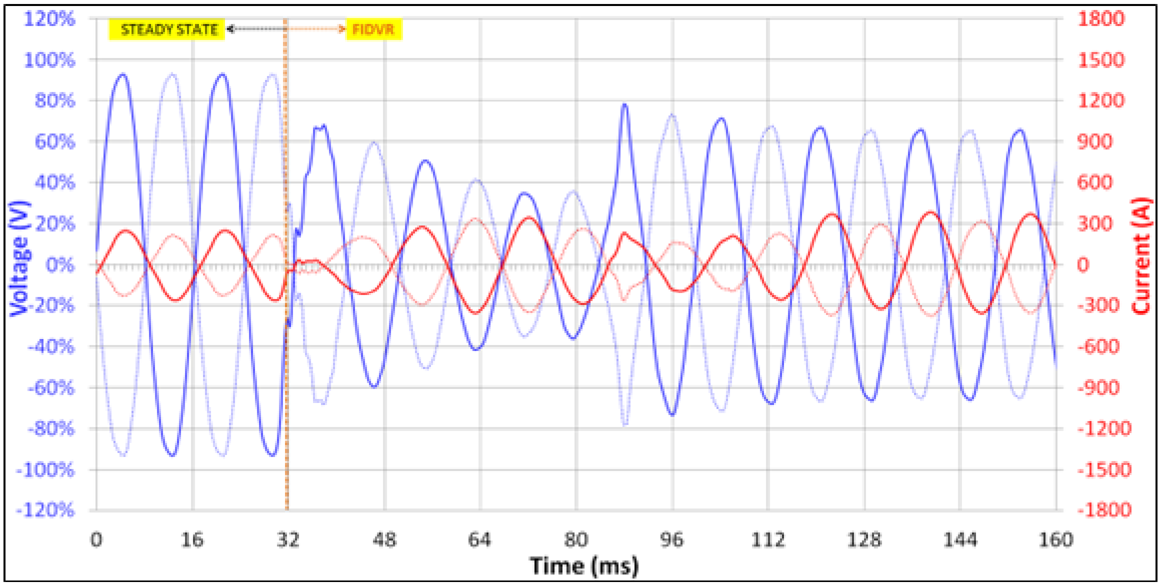

Figure 6-7 Event #3 (August 10, 14:14 PDT) Sinusoidal Data

6.4 Event #4 (August 11, 14:39 PDT)

The RMS data for Event #4 shown in Figure 6-8 exhibit these characteristics:

- This event may have spread to various distribution or subtransmission systems since it was observed and recorded by the PMU at the 115 kV level.
- Three faults, possibly caused by lightning strikes, were observed on this distribution circuit (two at the 1 second mark and one at 15 second mark of the figure below).
- The first fault did not stall RACs in this circuit because the circuit voltage was still above 78% of nominal.
- The second fault brought the voltage down to 45% where RAC loads stalled.
- P and Q increased significantly
    - o P=2.67X at 78%, 3 seconds after the FIDVR event began
    - o Q=6.28X at 78%, 3 seconds after the FIDVR event began
- The FIDVR event duration was approximately 9 seconds before reaching pre-event voltage.
- 70% of the load was lost due to RAC internal thermal protection switches by the end of the voltage recovery.
- A 5% overvoltage occurred at the end of the event due to sudden loss of load.

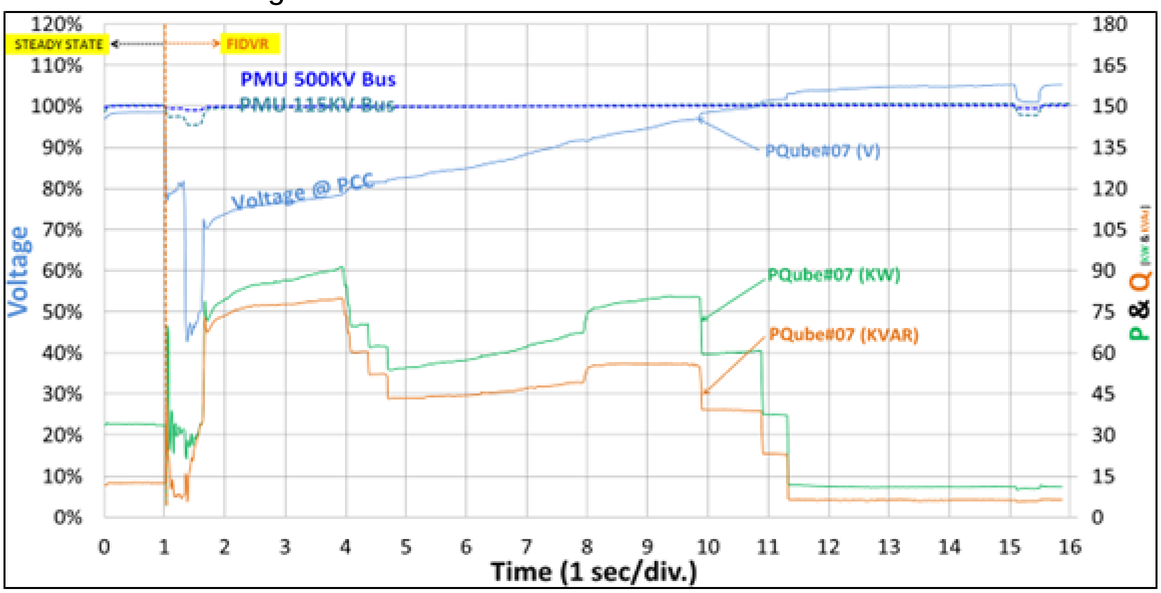

Figure 6-8 Event #4 (August 11, 14:39 PDT) RMS Data

According to this event's sinusoidal waveform data [Figure 6-9], this event may have started at an adjacent circuit since it did not immediately stall local RAC and the voltage only dropped to 80 percent with current similar to that of steady-state. In the middle of the sinusoidal plot, another event occurred with the voltage suppressed to less than 70 percent of normal. This low voltage caused RAC to stall and the current to increase significantly. The waveform peak current increased from 200 A to 850 A.

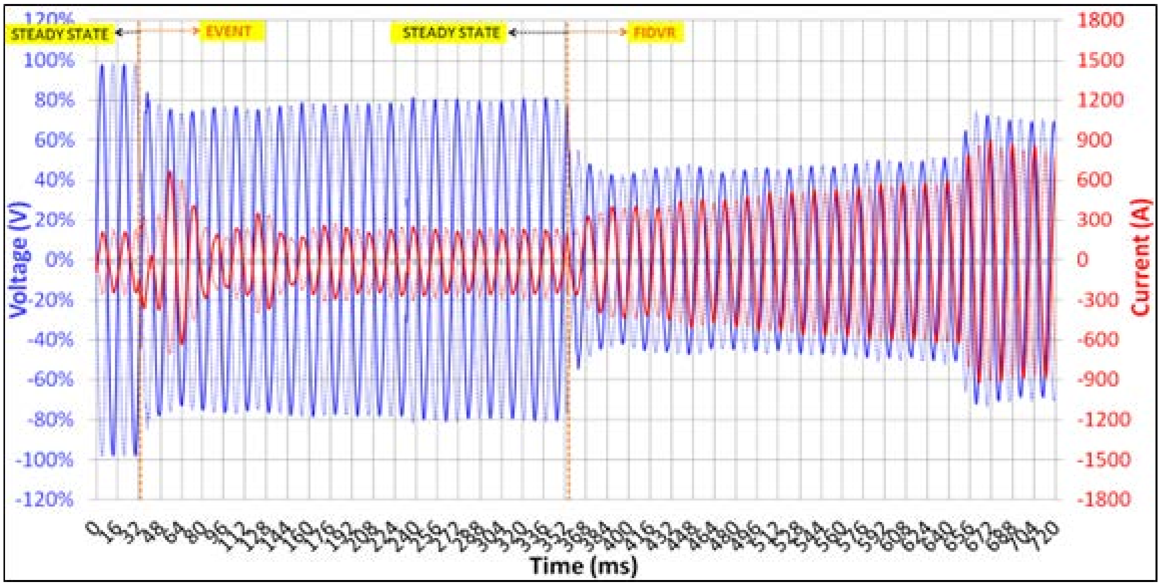

Figure 6-9 Event #4 (August 11, 14:39 PDT) Sinusoidal Data

According to this event's sinusoidal waveform data [Figure 6-10], the FIDVR event was initiated with a low voltage that started at **90 degrees** into the voltage waveform.

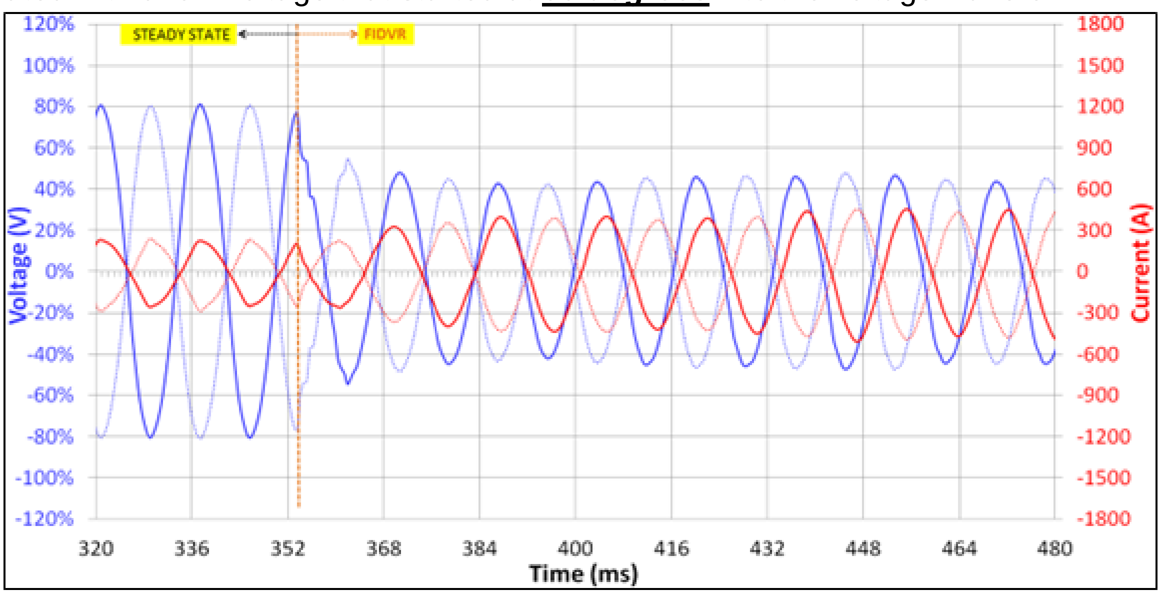

Figure 6-10 Event #4 (August 11, 14:39 PDT) Sinusoidal Data [zoomed-in]

6.5 Event #5 (August 12, 15:51 PDT)

RMS data for Event #5 shown in Figure 6-11 exhibit these characteristics:

- The event may have spread to various distribution or subtransmission systems since it was observed and recorded by the PMU at the 115 kV level.
- A fault caused voltage to dip to 35% of nominal, resulting in some load tripping and local RAC stalling right after fault clearance.
- P and Q increased significantly
  - P=1.837X at V=75%, 12.5 seconds after the FIDVR event began
  - Q=4.0X at V=75%, 12.5 seconds after the FIDVR event began
- The FIDVR event duration was approximately 15 seconds until the voltage recovered above 100%.
- 50% of the load was lost due to RAC internal thermal protection switches.
- An overvoltage of 17% above steady-state was observed on the distribution circuit after the loss of load.

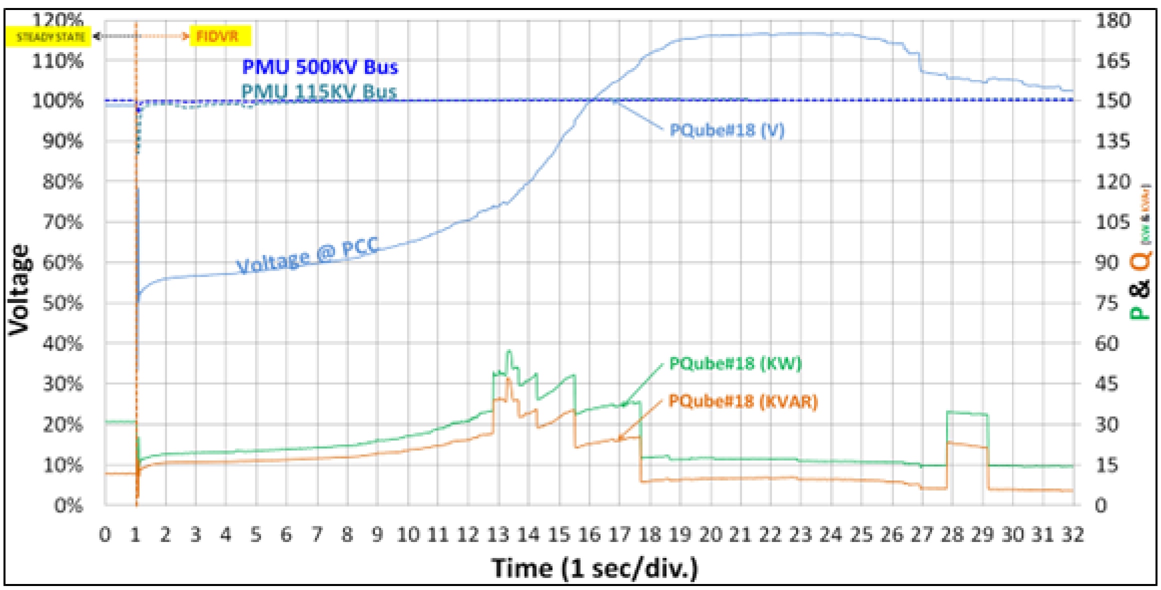

Figure 6-11 Event #5 (August 12, 15:51 PDT) RMS Data

According to this event's sinusoidal waveform data shown in Figure 6-12, the FIDVR event started at **<u>150 degrees</u>** past the zero crossing of the voltage waveform.

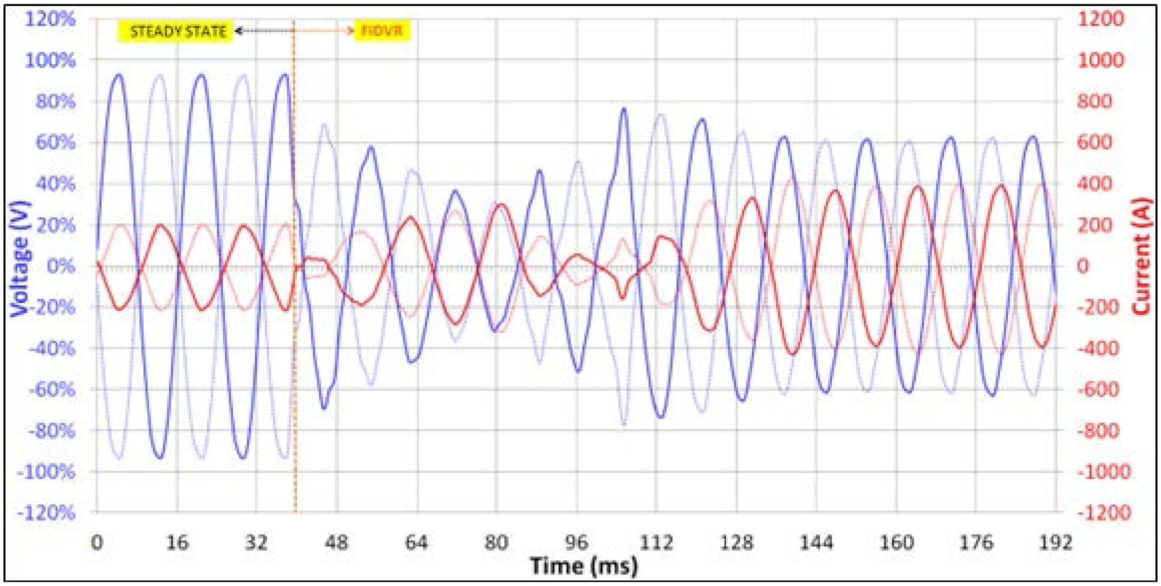

Figure 6-12 Event #5 (August 12, 15:51 PDT) Sinusoidal Data

6.6 Event #6 (August 12, 15:59 PDT)

Field operations personnel (FOP) state that this event happened when a small tornado knocked down subtransmission sections of the Valley system. The RMS data for Event #6 shown in Figure 6-13 exhibit these characteristics:

- The event spread into the subtransmission systems as evidenced by PMU and multiple PQ device recordings.
- A fault brought the voltage down as low as 30% where RACs stalled in several distribution circuits.
- Both 500 kV and 115 kV PMU signals dropped for more than 2 seconds due to communications problems during the low voltage.
- The 115 kV and PCC circuits took approximately 12 and 15 seconds to recover above 100% nominal voltage.
- The loss of the load provoked an overvoltage of 13% above steady-state on the distribution circuit and 3% on the subtransmission 115 kV bus.

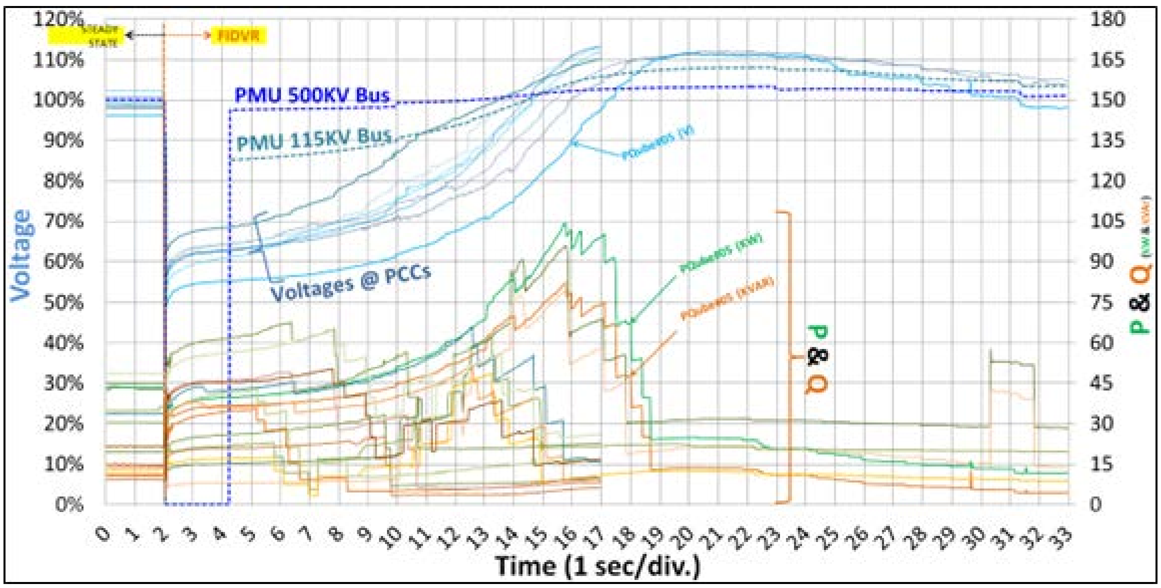

Figure 6-13 Event #6 (August 12, 15:59 PDT) RMS Data

The data show that the voltages go as low as 30 percent during the fault, which may be useful to set voltage ride through parameters.

In order to assess the events impacts at the PCC, the highest and lowest voltages are plotted in Figure 6-14. The circuit with the highest PCC voltage exhibits these characteristics:

- P and Q increased significantly,
  - o P=1.5X at V=72%, 4 seconds after the FIDVR event began
  - o Q=3.55X at V=72%, 4 seconds after the FIDVR event began
- The FIDVR event lasted approximately 12 seconds.
- 50% of load was lost due to RAC's TOPS.
- Circuit overvoltage reached 10% above steady-state where the PQ device stop recording.

The circuit with the lowest PCC voltage exhibited these characteristics:

- P and Q increased significantly
  - o P=2.30X at V=87%, 13.5 seconds after the FIDVR event began
  - o Q=7.30X at V=87%, 13.5 seconds after the FIDVR event began
- The FIDVR event lasted approximately 15 seconds.
- 75% of the load was lost due to RAC's TOPS.
- Circuit overvoltage rose to 12% above steady-state.

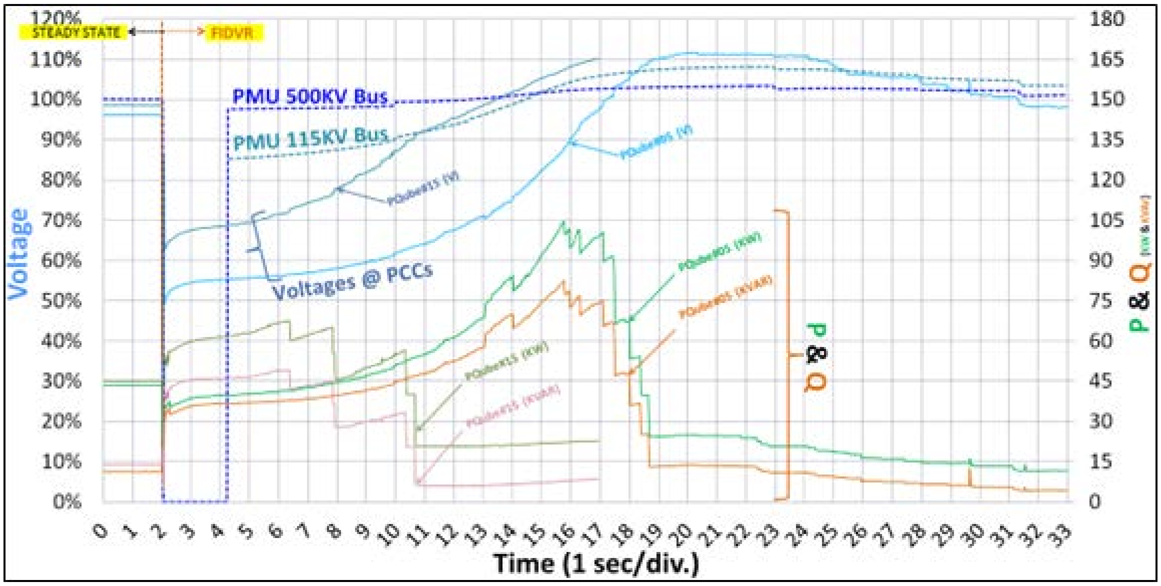

Figure 6-14 Event #6 (August 12, 15:59 PDT) Sinusoidal Data

According to this event's sinusoidal waveform data [Figure 6-15] the FIDVR event started at **<u>zero crossing</u>** of the voltage waveform.

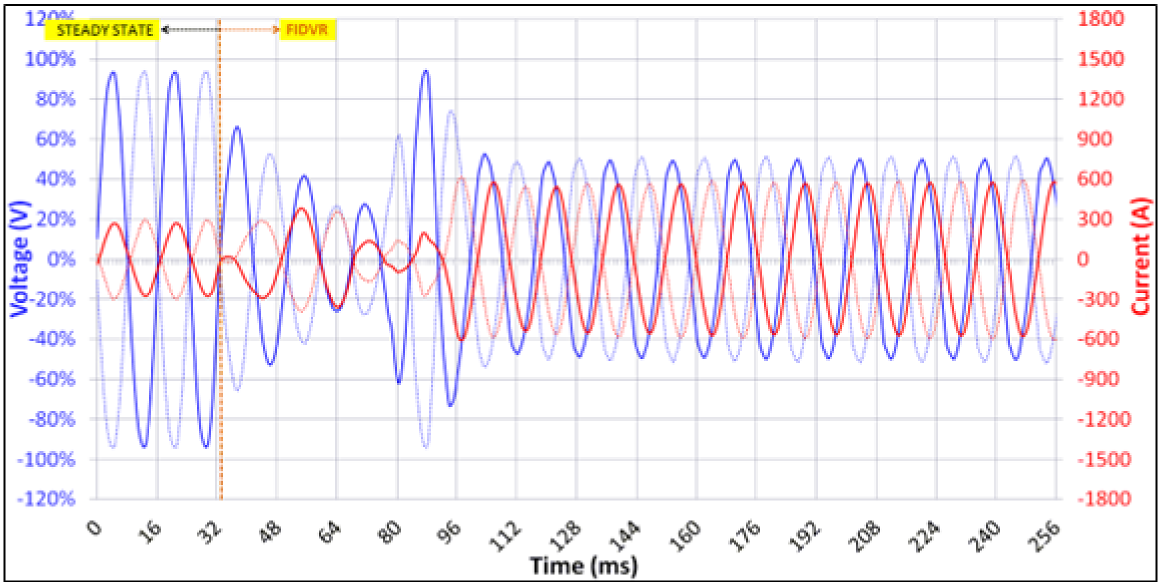

Figure 6-15 Event #6 (August 12, 15:59 PDT) Sinusoidal Data

6.7 Event #7 (August 12, 16:18 PDT)

This event happened about 18 minutes after the previous event. RMS data for Event #7 shown in Figure 6-16 exhibit these characteristics:

- The event spread in both subtransmission and distribution systems, as evidenced by PMU and multiple PQ device recordings.
- A fault brought the voltage down as low as 32% causing RACs to stall in multiple distribution circuits.
- Both 500 kV and 115 kV PMU signals dropped for more than 2 seconds due to communications problems during the low voltage.
- The 500 kV and 115 kV systems took approximately 10 and 11 seconds respectively to recover to steady-state voltage.
- The 240 V circuit took approximately 14 seconds to reach the steady-state voltage.
- The loss of the load provoked an overvoltage of 17% above steady-state in the distribution circuit, 6% at the subtransmission 115 kV bus, and 3% at the transmission bus 500 kV.

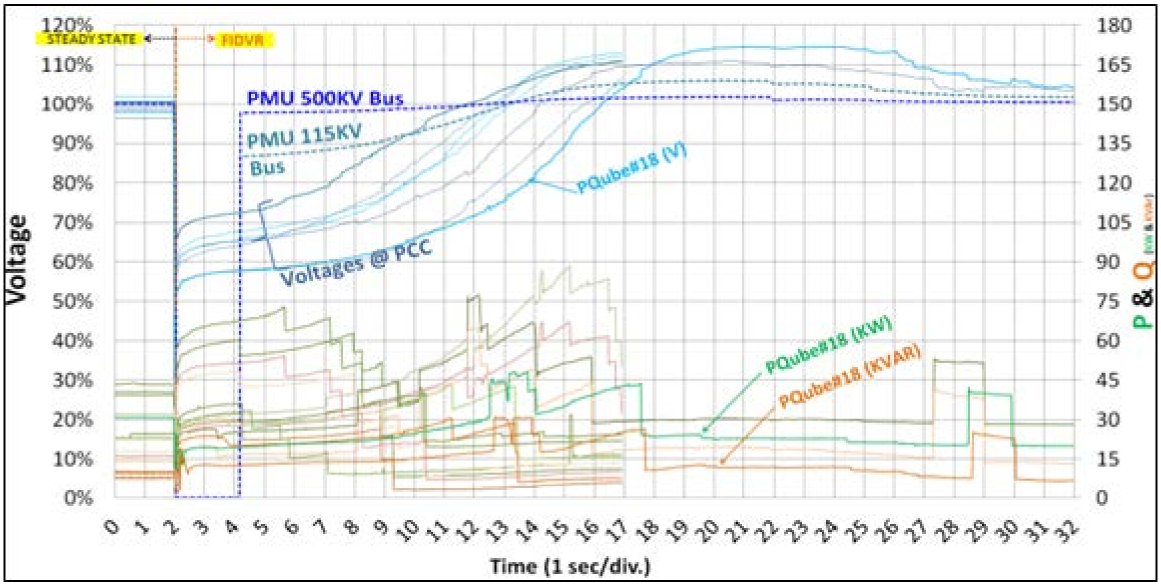

Figure 6-16 Event #7 (August 12, 16:18 PDT) RMS Data

In order to assess the event impacts at the PCC, the highest and lowest voltages are plotted in Figure 6-17. The circuit with the highest PCC voltage exhibits these characteristics:

- P and Q increased significantly
  - P=1.65X at V=74%, 13.5 seconds after the FIDVR event began
  - Q=3.33X at V=74%, 13.5 seconds after the FIDVR event began
- The FIDVR event lasted approximately10 seconds.
- 50% of the load was lost due to RAC's TOPS.
- Circuit overvoltage reached 11% above steady-state where the PQ device stop recording.

The circuit with the lowest PCC voltage exhibited these characteristics:

- P and Q increased significantly
  - P=1.55X at V=81%, 5 seconds after the FIDVR event began
  - Q=3.18X at V=81%, 5 seconds after the FIDVR event began
- The FIDVR event lasted approximately 15 seconds.
- 35% of the load was lost due to RAC's TOPS.
- Circuit voltage rose to 17% above nominal. Adjacent circuit overvoltages may have contributed to the magnitude of the overvoltage.

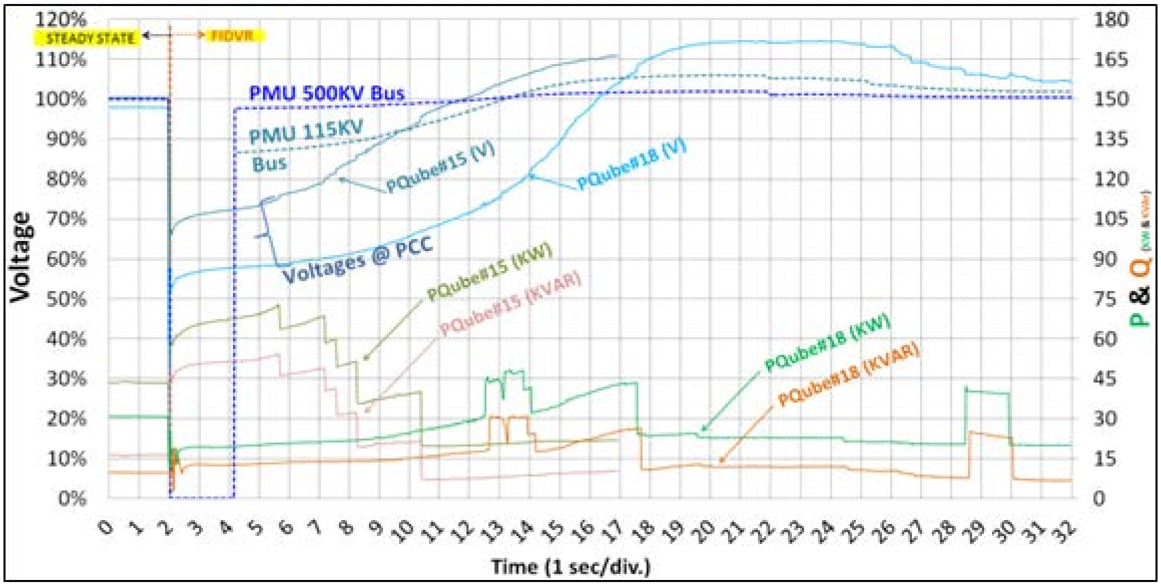

Figure 6-17 Event #7 (August 12, 16:18 PDT) RMS Data

According to this event's sinusoidal waveform data [Figure 6-18] the FIDVR event started at **60 degrees** past the zero crossing of the voltage waveform.

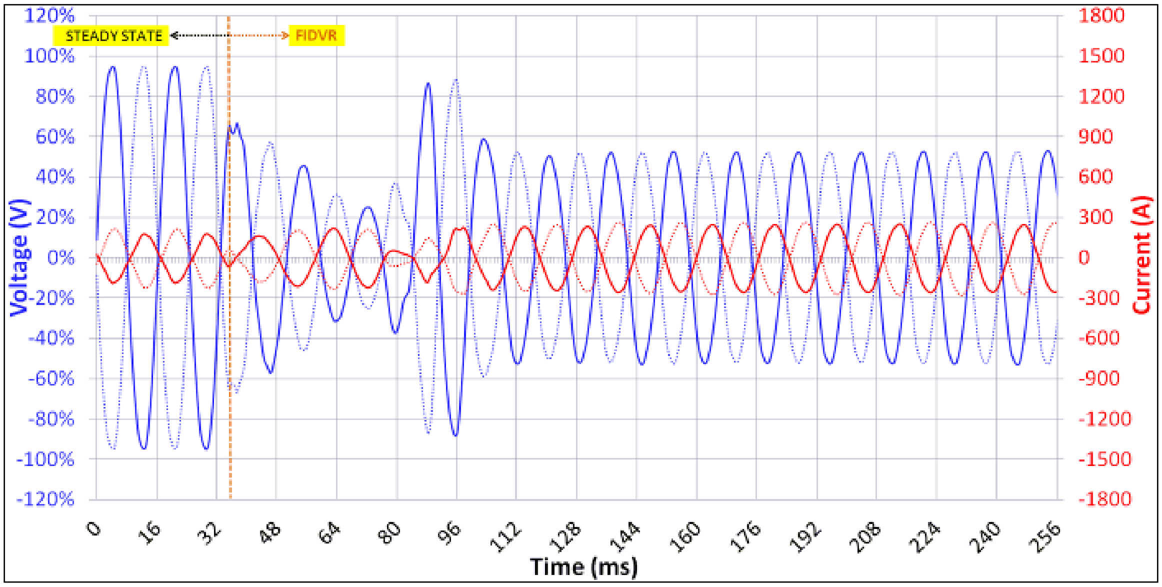

Figure 6-18 Event #7 (August 12, 16:18 PDT) Sinusoidal Data

6.8 Event #8 (August 30, 14:42 PDT)

The Grid Control Center (GCC) reported two 115 kV lines relaying in the Valley system during a lightning storm. The RMS data for Event #8 shown in Figure 6-19 exhibit these characteristics:

- The event spread through the subtransmission systems as evidenced by PMU and multiple PQ device recordings.
- A fault brought the voltage down as low as 30% where RACs stalled in several distribution circuits.
- Both 500 kV and 115 kV PMU signals dropped for more than 2 seconds due to communications problems during the low voltage.
- The 115 kV and PCC circuits took approximately 6 and 7 seconds respectively to recover to steady-state.
- The loss of the load provoked an overvoltage of 8% above steady-state on the distribution circuit and 2% on the subtransmission 115 kV bus.

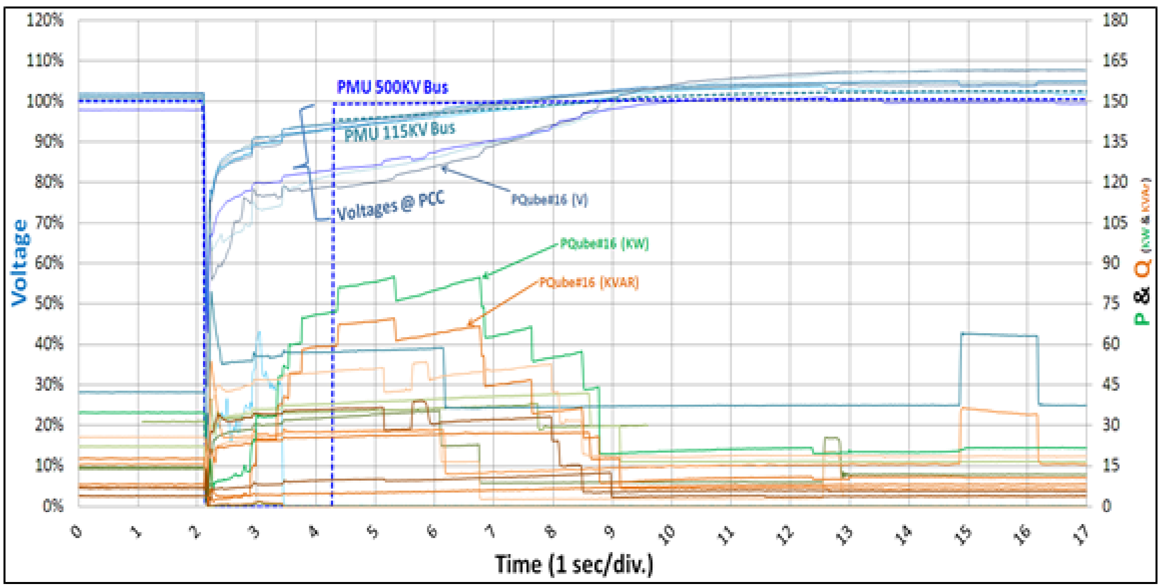

Figure 6-19 Event #8 (August 30, 14:42 PDT) RMS Data

In order to assess the events impacts at the PCC, the highest and lowest recovery voltages are plotted in Figure 6-20.

The circuit with the highest PCC voltage exhibits these characteristics:

- P and Q increased significantly,
  - o P=1.9X at V=67%, in the 1st second of the FIDVR event

- o Q=3.4X at V=67%, in the 1st second of the FIDVR event
- The FIDVR event lasted approximately 5 seconds.
- 11% of the load was lost due to RAC's TOPS.
- Circuit experienced overvoltage of 5% above steady-state.

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

- P and Q increased significantly
  - o P=2.5X at V=81%, 3 seconds after the FIDVR event began
  - o Q=3.9X at V=81%, 3 seconds after the FIDVR event began
- The FIDVR event lasted approximately 7 seconds.
- 42% of load was lost due to RAC's TOPS.
- Circuit experienced overvoltage of 8% above steady-state.

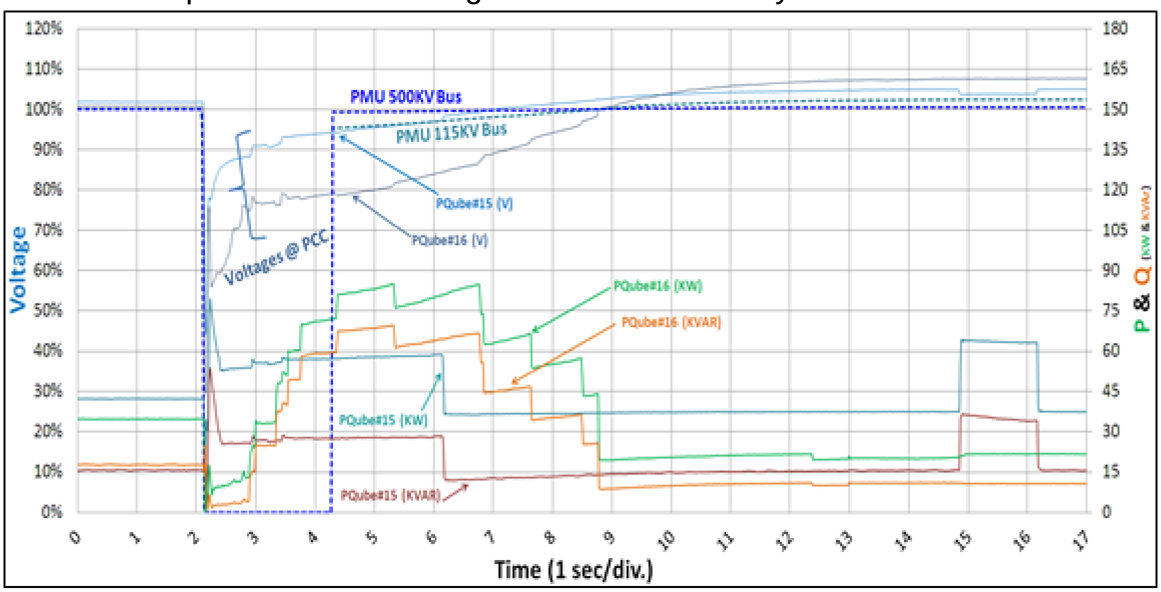

Figure 6-20 Event #8 (August 30, 14:42 PDT) RMS Data [two circuits]

The zoomed-in sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6-21] indicate that this FIDVR event was initiated at **110 degrees** on the voltage waveform.

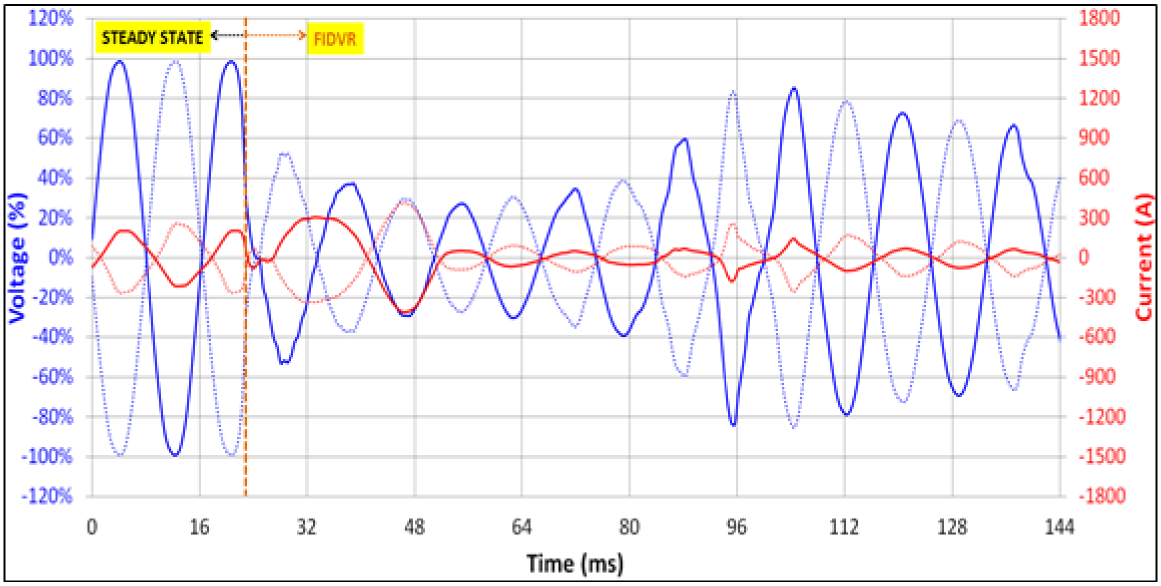

Figure 6-21 Event #8 (August 30, 14:42 PDT) Sinusoidal Data [zoomed-in]

The sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6-22] indicate that this FIDVR event may have started by the disconnection of voltage sensitive loads. This circuit was withdrawing about 200 amps-peak before the event and as high as 700 amps-peak during the event [not shown in this plot].

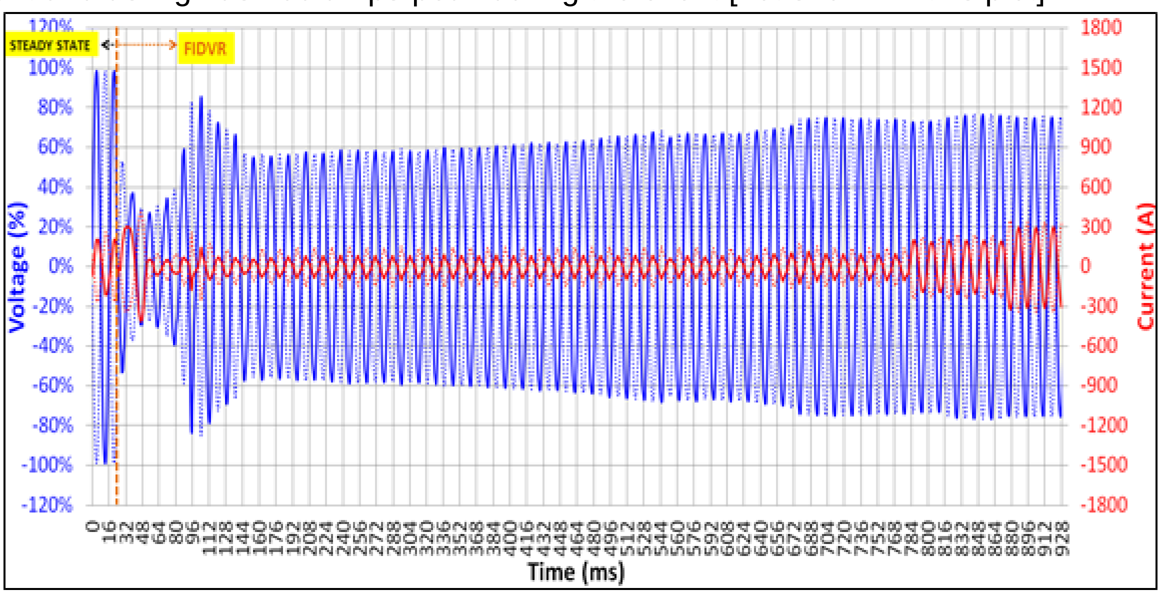

Figure 6-22 Event #8 (August 30, 14:42 PDT) Sinusoidal Data

6.9 Event #9 (August 30, 15:02PDT))

The Grid Control Center (GCC) reported one 115 kV line relaying in the Valley system during a lightning storm. The RMS data for Event #9 shown in Figure 6-23 exhibit these characteristics:

- The event spread to various distribution systems since it was observed and recorded by PMU at the 115 kV level and at multiple PQ devices.
- The fault brought the voltage down to 50% on one circuit where RACs stalled.
- P and Q increased significantly
  - o P=2.1X at V=90%, in the 1st second of the FIDVR event
  - o Q=2.9X at V=90%, in the 1st second of the FIDVR event
- The FIDVR event lasted approximately 3 seconds before reaching pre-event voltage.
- Loads start disconnecting approximately 1 second after the FIDVR event is triggered. At least two big residential loads tripped during the course of the event.
- By the end, 11% of the load was lost due to RAC internal thermal protection switches.
- No overvoltage was evidenced in this event.

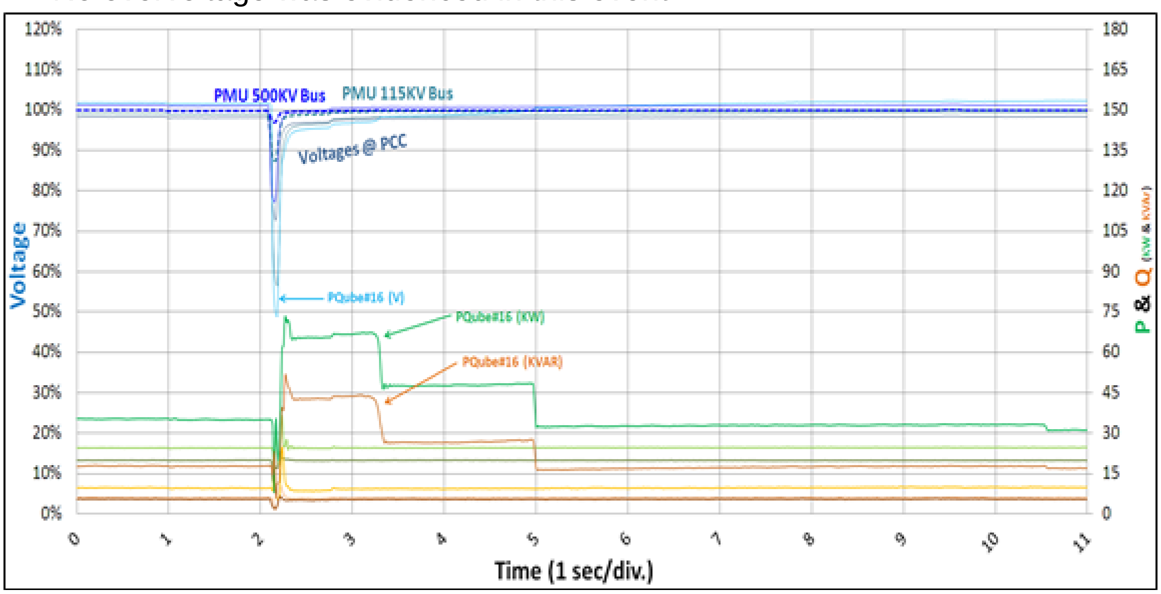

Figure 6-23 Event #9 (August 30, 15:02PDT) RMS Data

The zoomed-in sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6-24] indicate that this FIDVR event was initiated at **140 degrees** on the voltage waveform. For the first cycle the current was leading the voltage, but thereafter the current was lagging the voltage as before the event began.

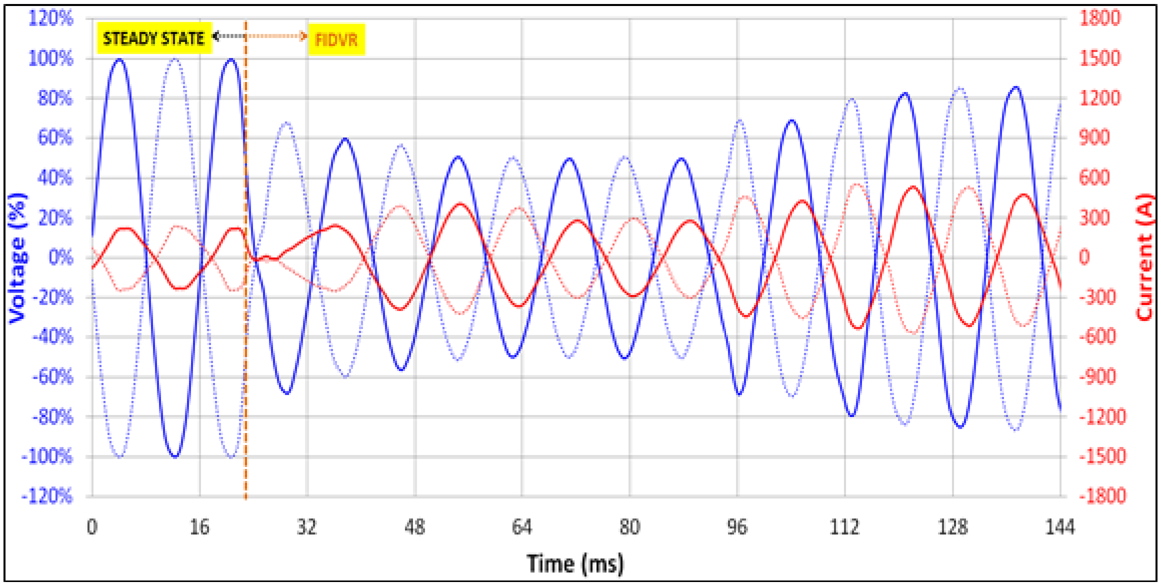

Figure 6-24 Event #9 (August 30, 15:02PDT) Sinusoidal Data [zoomed-in]

The current increased significantly during the event from about 200 amps-peaks to as high as 600 amps-peaks, as shown in Figure 6-25.

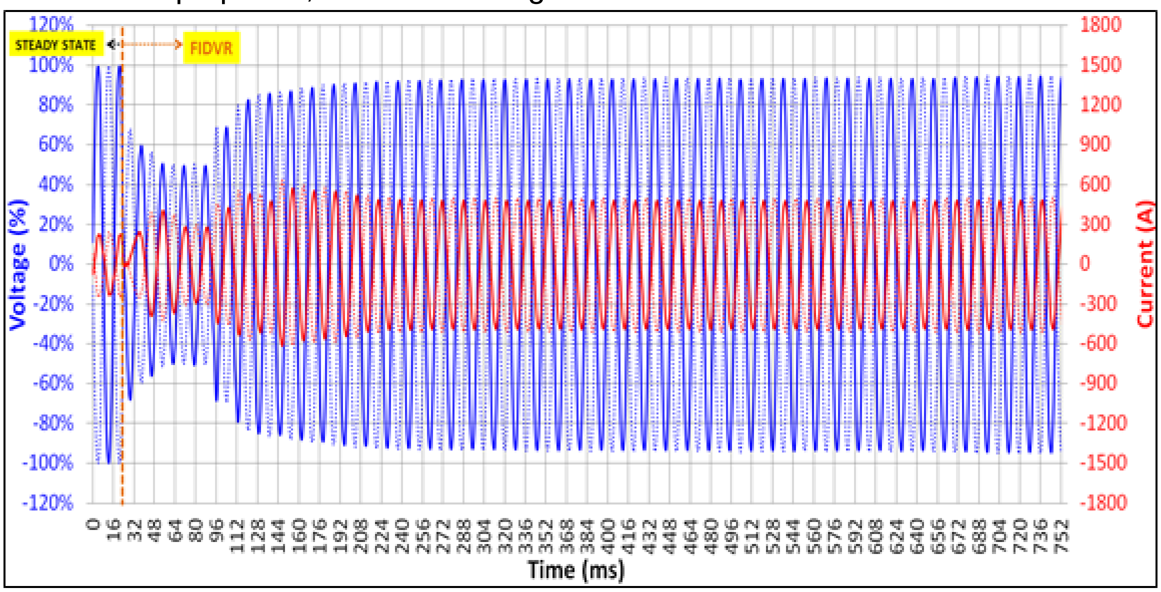

Figure 6-25 Event #9 (August 30, 15:02PDT) Sinusoidal Data

6.10 Event #10 (August 30, 15:22 PDT)

The RMS data for Event #10 shown in Figure 6-26 exhibit these characteristics:

- A fault caused by lightning strikes appeared only in the distribution circuit point of common coupling (PCC), but almost completely washed out in the PMU data.
- The fault brought the voltage down to 48% where RACs stalled.
- P and Q increased significantly
  - o P=2.3X at V=90%, in the 2nd second of the FIDVR event
  - o Q=3.5X at V=90%, in the 2nd second of the FIDVR event
- The FIDVR event lasted approximately 6.5 seconds before reaching pre-event voltage.
- Loads start disconnecting approximately 2 seconds after the FIDVR event is triggered with two drops in load.
- By the end, 36% of the load was lost due to RAC internal thermal protection switches.
- No overvoltage was evidenced in this event.

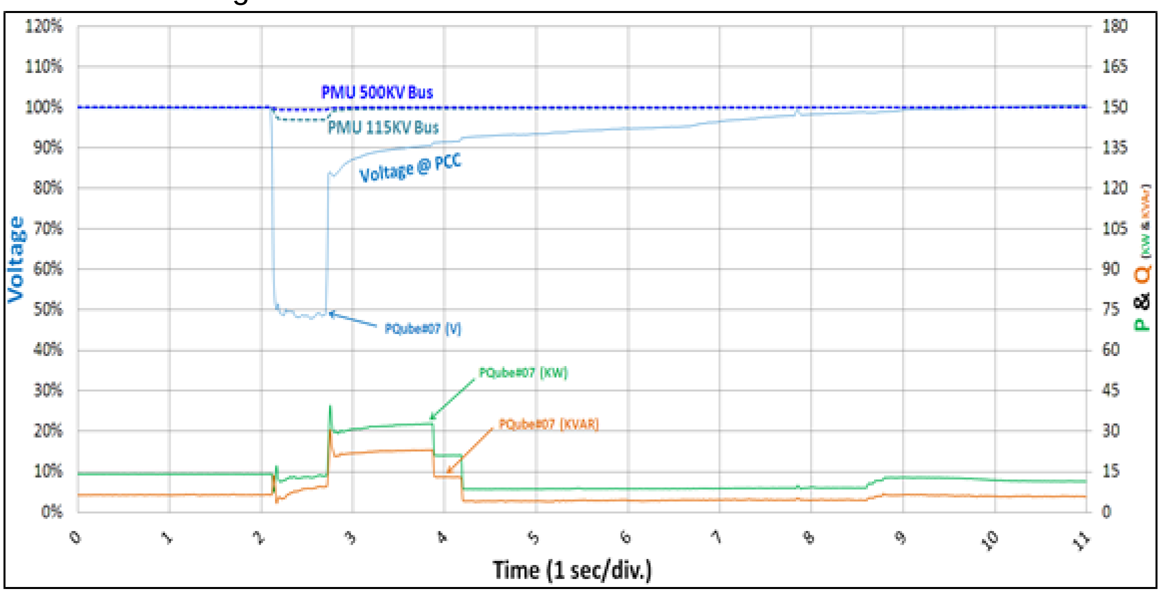

Figure 6-26 Event #10 (August 30, 15:22 PDT) Sinusoidal Data

The zoomed-in sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6-27] indicate that this FIDVR event was initiated at **<u>80 degrees</u>** on the voltage waveform. It seems that for the first cycle the current was leading the voltage, but thereafter the current was lagging the voltage as before the event began.

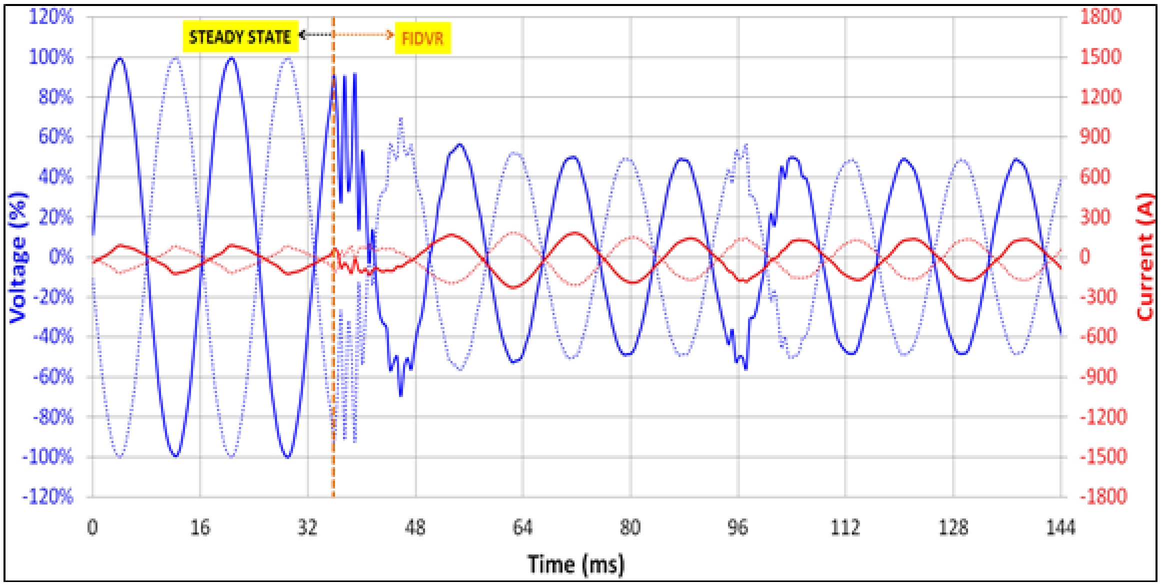

Figure 6-27 Event #9 (August 30, 15:22 PDT) Sinusoidal Data

The current increased significantly during the event from about 100 amps-peaks to as high as 350 amps-peaks, as shown in Figure 6-28.

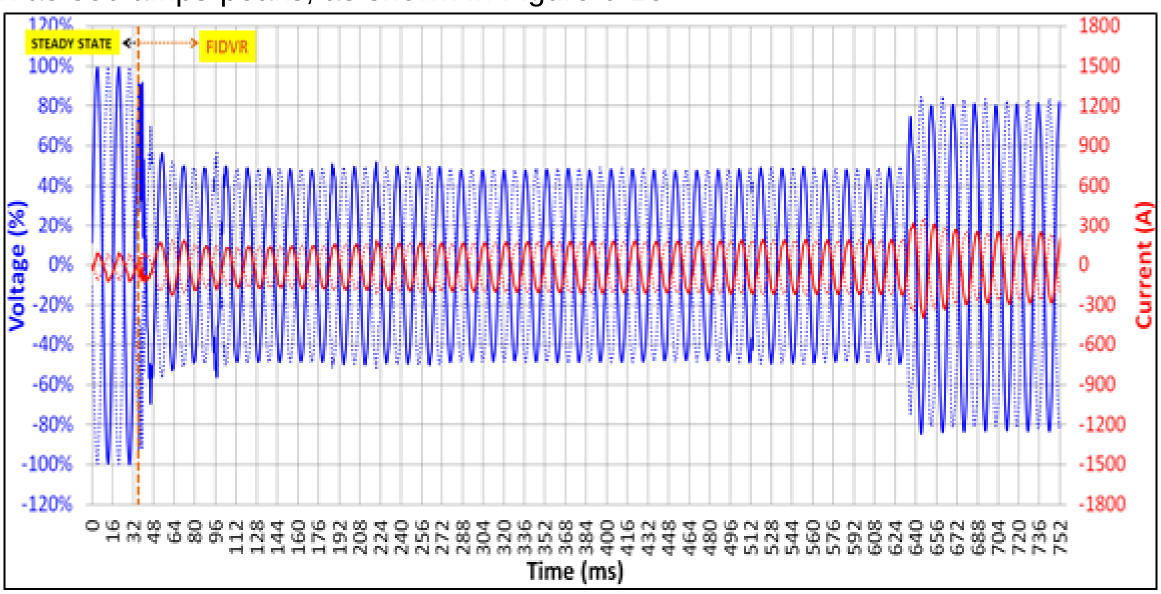

Figure 6-28 Event #9 (August 30, 15:22 PDT) Sinusoidal Data

6.11 Event #11 (August 30, 15:46 PDT)

The Grid Control Center (GCC) reported a 115 kV line relaying in the Valley system during a lightning storm. The RMS data for Event #11 shown in Figure 6-29 exhibit these characteristics:

- The event spread through the distribution systems as evidenced by multiple PQ device recordings, but only slight deviation from PMU data.
- A fault brought the voltage down as low as 40% where RACs stalled in several distribution circuits.
- Both 500 kV and 115 kV PMU only dropped down to 96% voltage.
- The PCC circuits took approximately between 5.5 and 7 seconds respectively to recover to pre-event voltages.
- No significant overvoltage was observed in this event (only 3% above steady-state).

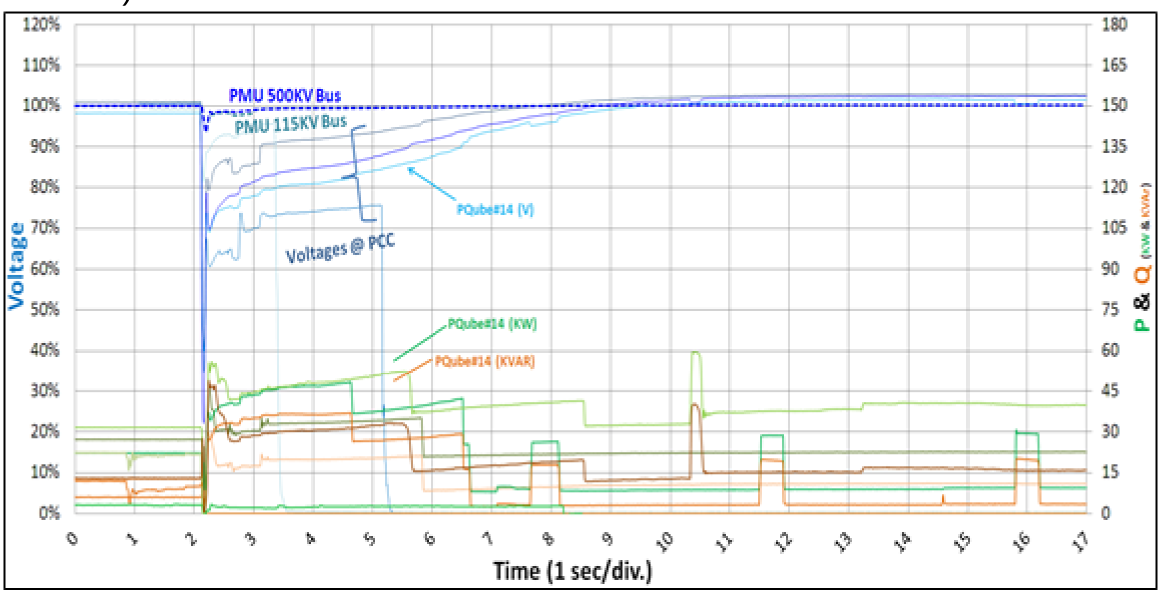

Figure 6-29 Event #11 (August 30, 15:46 PDT) RMS Data

In order to assess the events impacts at the PCC the highest and lowest recovery voltages are plotted in Figure 6-30. The circuit with the highest PCC voltage exhibits these characteristics:

- P and Q increased significantly
  - P=1.3X at V=92%, 1 second after the FIDVR event began
  - Q=1.7X at V=92%, 1 second after the FIDVR event began
- The FIDVR event lasted approximately 5.5 seconds.

- 23% of the load was lost due to RAC's TOPS.

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

- P and Q increased significantly
  - o P=2.2X at V=82%, in the 3rd second of the FIDVR event
  - o Q=6X at V=82%, in the 3rd second of the FIDVR event
- The FIDVR event lasted approximately 7 seconds.
- 63% of load was lost due to RAC's TOPS.

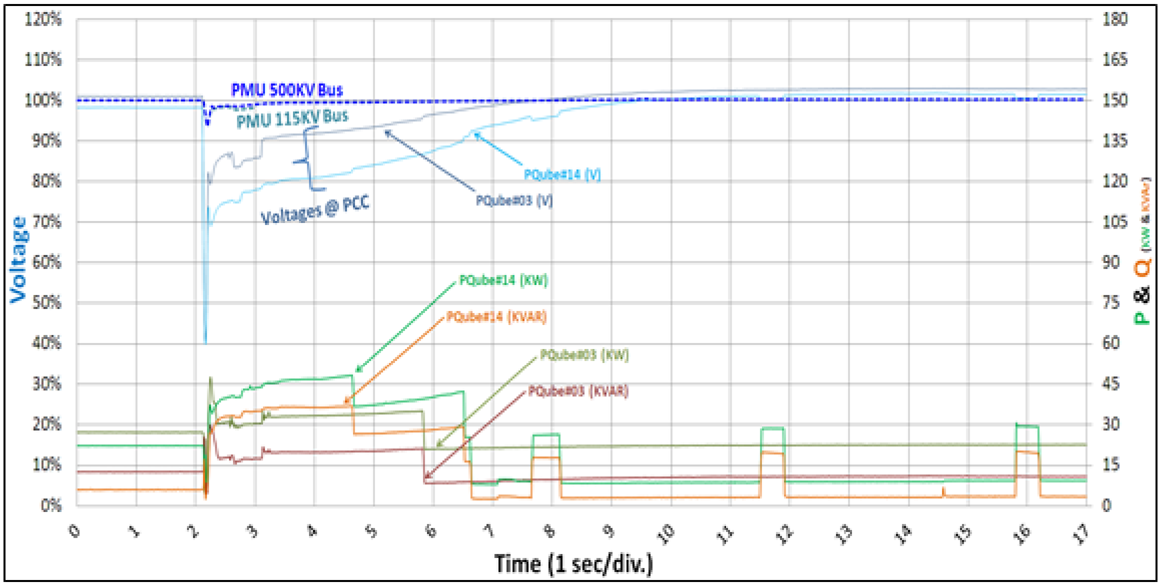

Figure 6-30 Event #11 (August 30, 15:46 PDT) RMS Data [two circuits]

The zoomed-in sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6-31] indicate that this FIDVR event was initiated at **20 degrees** on the voltage waveform. It seems that for the first cycle the current was leading the voltage, but thereafter the current was lagging the voltage as before the event began.

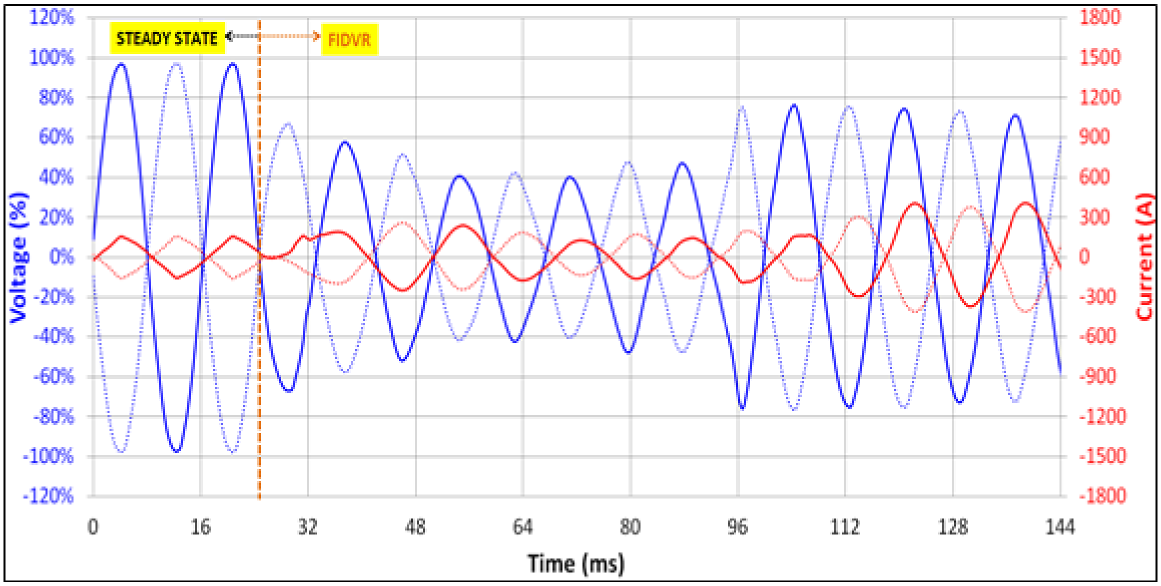

Figure 6-31 Event #11 (August 30, 15:46 PDT) Sinusoidal Data [zoomed-in]

The current increased significantly during the event from about 150 amps-peaks to as high as 400 amps-peaks, as shown in Figure 6-32.

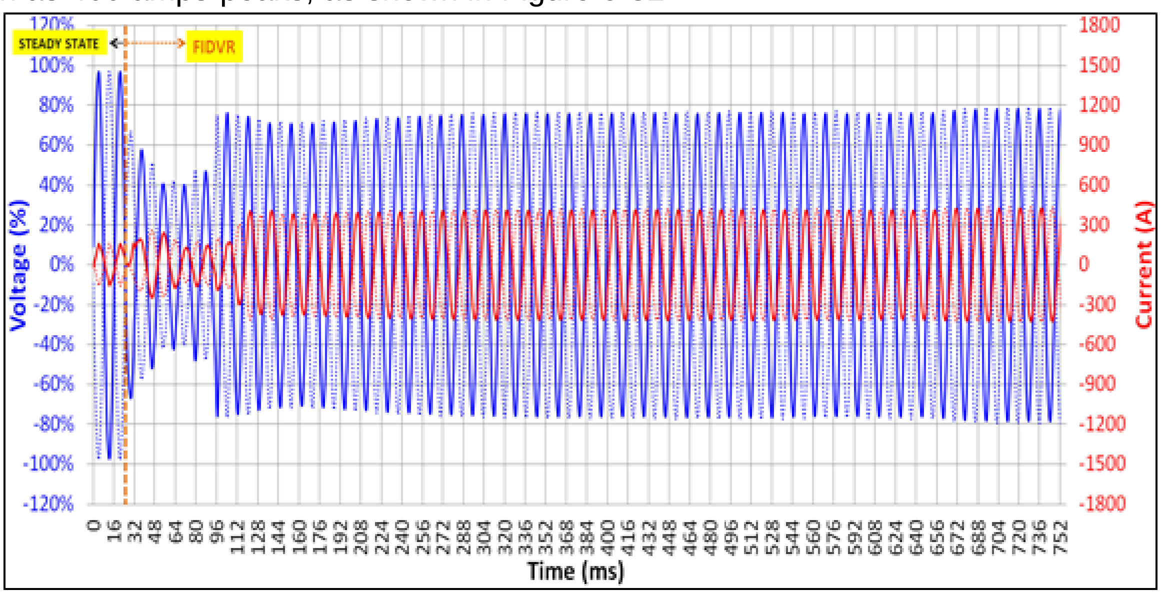

Figure 6-32 Event #11 (August 30, 15:46 PDT) Sinusoidal Data

6.12 Event #12 (August 30, 16:00 PDT)

The Grid Control Center (GCC) reported a 115 kV line relaying in the Valley system during a lightning storm. The RMS data for Event #12 shown in Figure 6-33 exhibit these characteristics:

- The event spread through the distribution systems as evidenced by multiple PQ device recordings, but only slight deviation from PMU data.
- The fault brought the voltage down to 35% where RACs stalled.
- P and Q increased significantly
  - o P=1.5X at V=92%, in the 5th second of the FIDVR event
  - o Q=2X at V=92%, in the 5th second of the FIDVR event
- The FIDVR event lasted approximately 7 seconds before reaching pre-event voltage.
- Loads start disconnecting approximately 5 seconds after the FIDVR event is triggered.
- Load goes back close to steady-state after the event.
- No significant overvoltage was evidenced in this event.

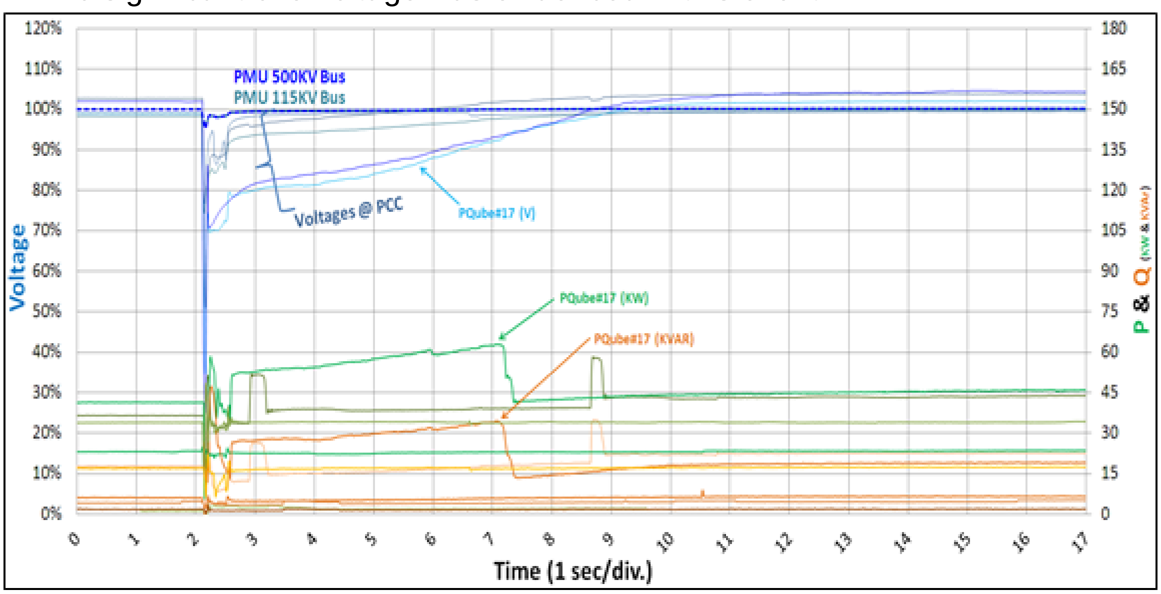

Figure 6-33 Event #12 (August 30, 16:00 PDT) RMS Data

Figure 6-34 show the tow distribution circuits that were affected during this event.

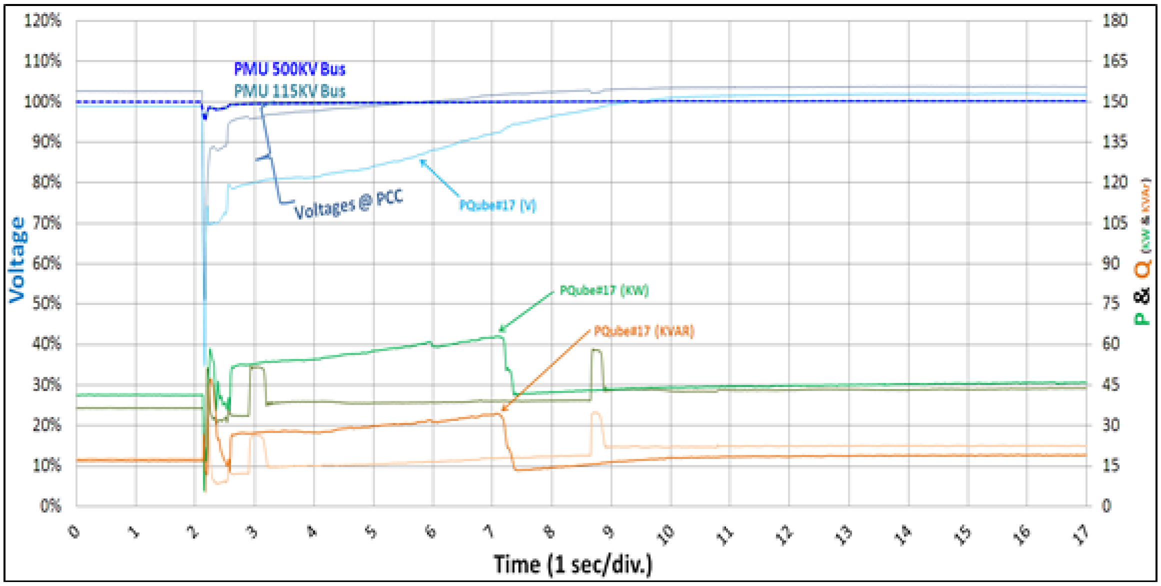

Figure 6-34 Event #12 (August 30, 16:00 PDT) RMS Data [two circuits]

The zoomed-in sinusoidal waveform data of the PQ device recorded the lowest voltage circuit [Figure 6-35] indicating that this FIDVR event was initiated at **90 degrees** on the voltage waveform. It seems that for the first cycle the current was leading the voltage, but thereafter the current was lagging the voltage as before the event began.

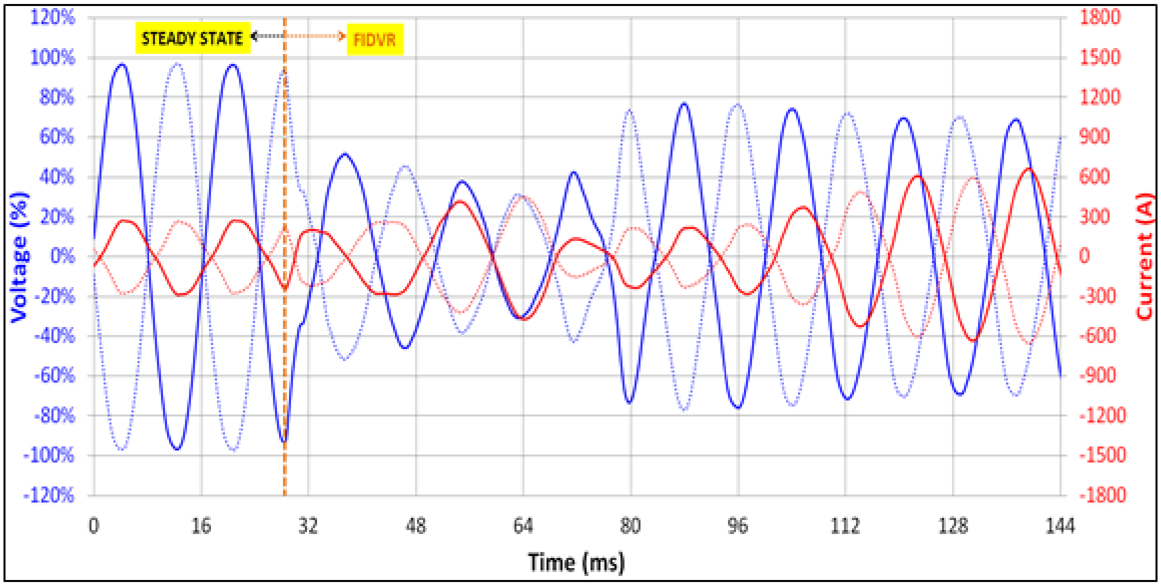

Figure 6-35 Event #12 (August 30, 16:00 PDT) Sinusoidal Data [zoomed-in]

The current increased significantly during the event from about 280 amps-peaks to as high as 650 amps-peaks, as shown in Figure 6-36.

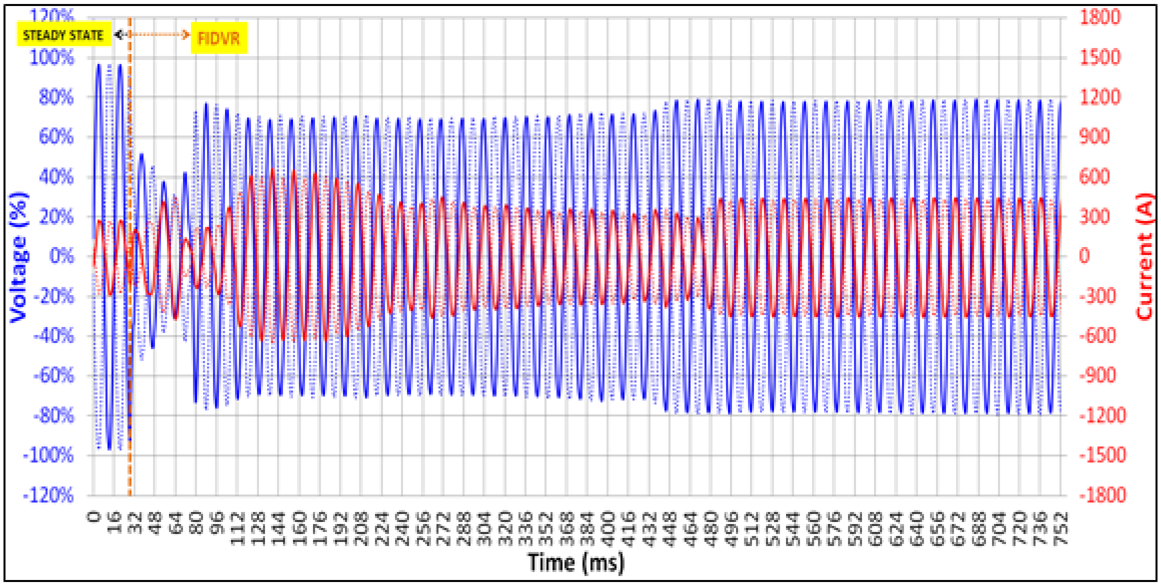

Figure 6-36 Event #12 (August 30, 16:00 PDT) Sinusoidal Data

7.0 CONCLUSIONS AND RECOMMENDATIONS

FIDVR events occur more often than previously expected during monsoon weather conditions 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.
- A majority of the FIDVR events occurred on the Section A&B Valley 115 kV bus sub-transmission network that covers the east 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 is 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.

Table 7-1 summarizes the voltage dips and real and reactive power measurements recorded before and during a FIDVR event. This data can be used to validate distribution system models with significant levels of RAC load. Additional monitoring to better characterize the behavior of distribution systems was installed in 2013. While this RMS data can be used for steady-state modeling, the sinusoidal data can be used for transient modeling using tools like PSCAD.

Table 7-1 FIDVR Event Summary

	AT STEADY STATE			During FIDVR		
Event #	**V(%)**	**P(KW)**	**Q(KVAR)**	**V(%)**	**P(KW)**	**Q(KVAR)**
1	97	30.5	8.5	90	82	69.4
2	96	53.3	15.5	85	94.5	68.5
3	96	36.0	11.2	84	63.4	43.8
4	98	34.0	12.7	78	90.8	79.8
5	99	30.8	11.9	74	49.3	39.6
6_15	99	44.7	14.1	72	67.7	48.8
6_05	96	44.7	11.3	87	103.9	82.2
7_18	100	30.8	9.6	81	47.5	30.2
7_15	100	43.8	16.1	74	72.2	53.9
8_15	102	42.2	15.8	67	79.2	53.8
8_16	101	34.7	17.7	81	85.1	69.5
9_16	102	35.1	17.9	90	73.2	51.6
10	100	14.1	6.5	90	32.7	22.9
11_03	101	27.3	12.6	92	34.8	21.2
11_14	98	22.3	6.1	82	48.0	36.7
12_17	100	41.4	17.1	92	63.0	34.4

Field operations personnel (FOP) provided valuable information about these events. They noted the larger events in the field (Event #6 and #7), but not localized events affecting only small areas. FOP claim that FIDVR events usually provoke:

- Distribution fuses blowing
- Automatic re-closers (AR) opening

This happens because the distribution circuits are typically run close to or above their limits. Most events took place in the eastern portion of the Valley system where monsoon precipitations are more likely to occur, rather than in the western part of the Valley system.

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-though (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.

8.0 LESSONS LEARNED

Analyzing these FIDVR events resulted in two lessons learned for future studies.

1. Both voltage and current data must be captured, RMS and sinusoidal, to fully assess the effects of FIDVR events.
2. Different PQ recorders must be synchronized to compare events in different distribution circuits.