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# Field Demonstration of Smart Inverter Autonomous Voltage Support using Combined Volt-Watt and Volt-VAR Curves

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## SUMMARY

With increasing penetration of distributed energy resources (DERs), utilities are exploring solutions to mitigate adverse impacts to the reliability of power delivery. In the California solar power industry, smart inverters (SIs) are being leveraged to accomplish this through autonomous voltage support functions including active power curtailment (Volt-Watt) and reactive power management (Volt-VAR). However, the application of these smart inverter functions has the potential of curtailing customer production and impacting their return on investment, which is a growing concern in the industry.

Through California's Electric Program Investment Charge (EPIC) program, Pacific Gas and Electric (PG&E) is executing a field demonstration that explores various Volt-Watt and Volt-VAR curve settings on 3-phase smart inverters for commercial/industrial photovoltaic (PV) installations, with the goal of analyzing which curve settings are most effective in managing voltage while minimizing customer curtailment. Preliminary results show that:

- Smart inverters are effectively able to follow Volt-Watt and Volt-VAR curve settings
- Customer curtailment due to the smart inverter settings is minimal
- Current proposed Volt-Watt and Volt-VAR settings may not be enough to mitigate voltage issues
- Voltage unbalance may affect the efficacy of smart inverter settings
- While smart inverters may contribute towards enhanced voltage management, a study of local effects and feeder state often have greater influence than application of the smart inverter functions

The field demonstration is ongoing and will conclude in September 2018.

## KEYWORDS

Smart Inverter, Volt-Watt, Volt-VAR, Active Power Curtailment, Reactive Power Support

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# 1. Introduction

PG&E is conducting a field demonstration of 3-phase smart inverters (SIs) for commercial and industrial customers in California's Central Valley from January through September 2018. The project seeks to further learnings on SI functions, implementation and control on a feeder with high voltage and high photovoltaic (PV) penetration. PG&E has partnered with a local PV system installer and customers with interconnected PV at 14 sites on a rural feeder to retrofit SIs by providing a firmware upgrade to existing equipment. These upgrades allowed PG&E to deploy Volt-Watt and Volt-VAR curves to the SIs. The 14 demonstration sites are agriculture-based and range in PV size from 100kW to 1MW. The total amount of DER generation controllable through the demonstration accounts for 35% of the feeder capacity. This penetration level will allow PG&E to explore effects of SI settings on the secondary side of the distribution transformer, at the point of common coupling (PCC) to the grid, and on the primary side of the distribution transformer at various locations along the distribution feeder.

The field demonstration is divided into three phases. In Phase 1, the system configuration is characterized by manual interaction with the SIs. The SIs are locally configured and data is manually retrieved from each of the 14 sites and is post-processed and analyzed at a later date. During this phase, a single set of Volt-Watt and Volt-VAR curves was executed on the SIs. Phase 1 concluded once reconductoring activities, scheduled separately from the demonstration goals, began.

In Phase 2, the system configuration continues to involve manual interaction but also includes cycling through different Volt-Watt and Volt-VAR curve settings on a weekly basis. Phase 2 begins once reconductoring activities on the circuit conclude.

In Phase 3, the system configuration includes the addition of a web-based, vendor-agnostic aggregation platform with the ability to remotely deploy curve settings and retrieve data from the SIs. This phase involves daily cycling of the various Volt-Watt and Volt-VAR curve settings.

This paper presents initial learnings from Phase 1 of the field demonstration and attempts to address the following questions:

- Is the SI able to follow the Volt-Watt and Volt-VAR curves without interaction/interference?
- What is the ability of the SI or grouping of SIs to move voltage as measured at the PCC using the Volt-Watt and Volt-VAR functions?
- What is the impact of the Volt-Watt and Volt-VAR functions on the feeder level?
- What is the effect of executing Volt-Watt and Volt-VAR on customer curtailment?

Further study is needed and a conclusive review will be executed upon conclusion of the field demonstration in late 2018.

# 2. Field Demonstration and Test Cases

The field demonstration involved 14 individual customer sites on a single 21kV distribution feeder. Each customer site had between 4 and 41 individual PV inverters for a total of 179 SMA Sunny Tripower 3-phase inverters. The inverters ranged in size from 12 to 30 kVA, with most of the inverters being 24kVA or 30kVA maximum output with the ability to support power factor ranges of 0.8 leading/lagging. A total of 4.5MW full production capacity was available with all assets online and all sites fully operational. Figure 1 shows a map of the pilot sites and the feeder substation, with the circle size reflective of PV size.

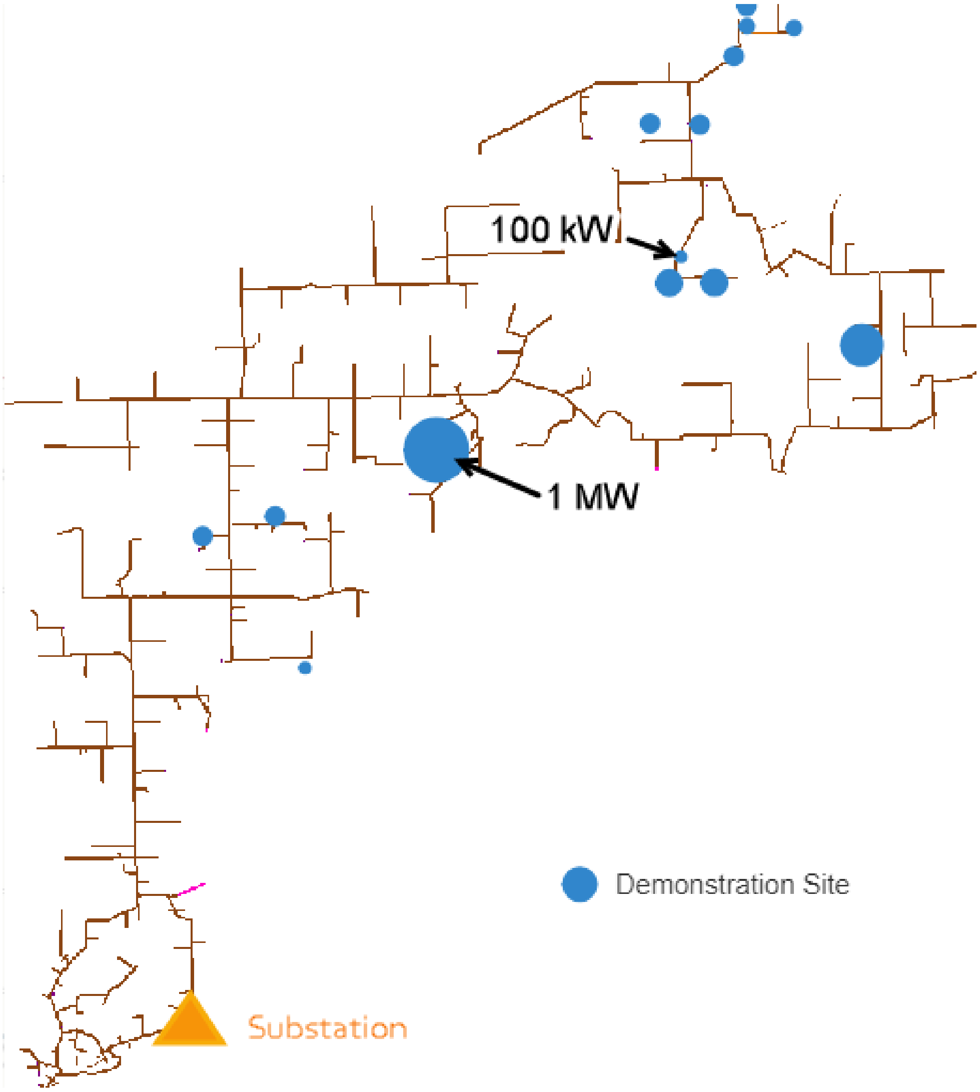


**Figure 1: Map of demonstration sites and feeder substation with circle size reflective of PV size**

The field demonstration data was gathered at the SI and the PCC at each site. It consisted of the inverter measurements, provided over 10-minute intervals, and of measurements at the PCC provided either by a customer smart meter or a field-installed power quality meter (PQM). The customer smart meter data was provided at 15-minute intervals, and the PQM data was provided at 1-minute intervals.

Phase 1 of the project ran from late January through early April 2018, with a staggered introduction of each of the 14 sites to the demonstration. During Phase 1, the inverters were programmed with a single Volt-Watt and Volt-VAR curve set as shown in Figure 2.

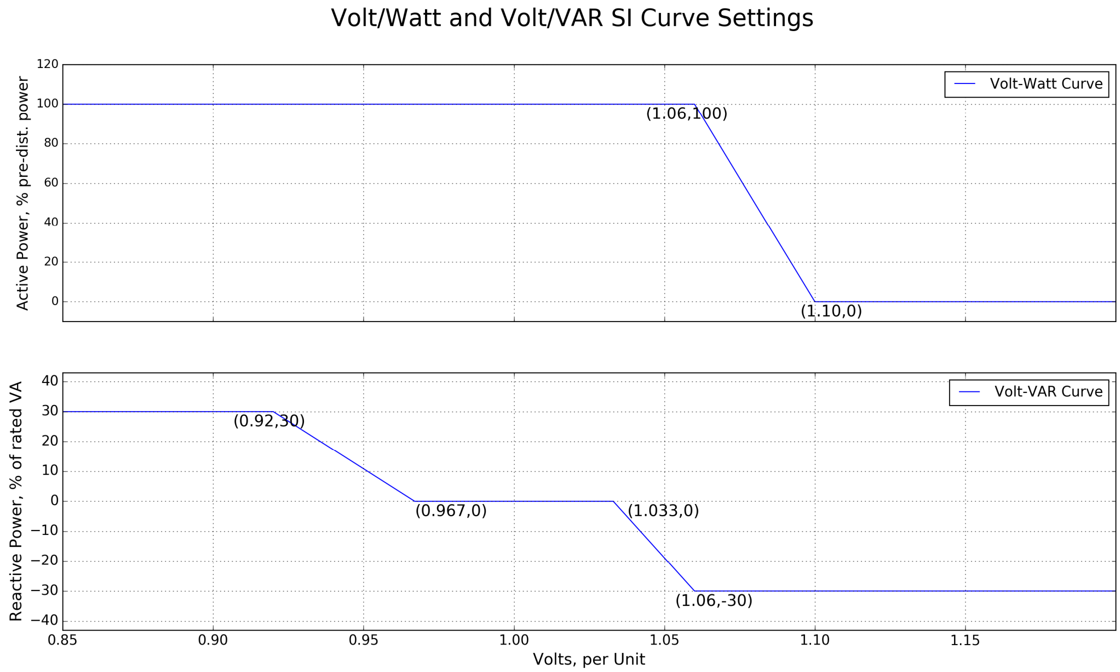


**Figure 2: Phase 1 Volt-Watt (top) and Volt-VAR (bottom) curve settings**

# 3. Results

## 3.1. SI Ability to Follow Volt-Watt and Volt-VAR

Addressing the question of the SI's ability to follow the Volt-Watt/Volt-VAR curves required forming a tolerance around the curve. This was derived using SMA's guidance on the limits of accuracy around their voltage (+/-2% AC Volts) and power measurements (+5% rated power). The SMA SIs use average RMS voltage from the 3 phases as the control parameter in determining how to follow the Volt-Watt/Volt-VAR curves. The inverters used percent of pre-disturbance power ($P_{pre}$) in determining how to follow the Volt-Watt curve.

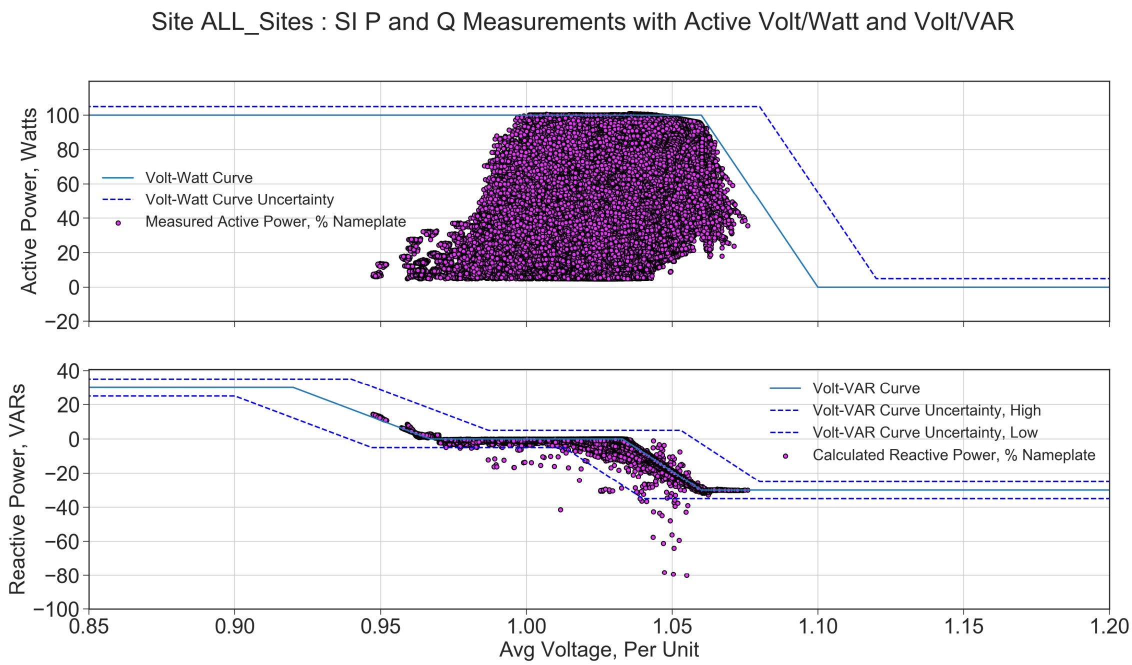


**Figure 3: SI data across all sites plotted against the active Volt-Watt and Volt-VAR settings, along with the tolerance bounds around the curve settings**

Figure 3 shows the SI's effectiveness in executing the Volt-Watt and Volt-VAR curves within the tolerance bounds. Figure 3 includes data from all active SIs across the demonstration sites.

With regards to Volt-Watt, all the data points fell below the Volt-Watt curve, suggesting appropriate behavior. Given that the inverters were programmed to use $P_{pre}$ in following the Volt-Watt curve and the limitations on the fidelity of the 10-minute data recorded by the SIs, it was difficult to decisively determine whether the SIs followed the curve. In Phases 2 and 3 of the field demonstration, the inverters will be programmed to follow Volt-Watt using percent of rated power output (Prated), which will clearly answer this question.

With regards to Volt-VAR, while the majority of data fell within the tolerance bounds, there were data points that did not. Of the 500,000 data points gathered across the Phase 1 demonstration, approximately 50 data points fell outside the tolerance, which may be considered negligible. Also contributing to the uncertainty was the fact that reactive power was calculated during post-processing rather than by the SI. During Phase 3 of the project, reactive power calculated by the SI will be available for further investigation.

## 3.2. SI Ability to Affect Voltage at the PCC

While this question was not directly answered in Phase 1 as there was no baseline data with no curve settings running to compare against, the Phase 1 data could be analyzed to understand the effectiveness of the curve settings selected in managing voltage at the PCC to PG&E Electric Rule No. 2 (Rule 2) limits, which mandate that the utility shall maintain voltage at the PCC to +/-5% of nominal voltage. Figure 4 is a histogram of the data from a single site showing bins of voltage 0.01Vp.u. wide and the percent of occurrences of that voltage value over the Phase 1 period. Voltage at the site ranged from 0.99Vp.u. to 1.07Vp.u., with the majority of data falling between 1.01 to 1.05Vp.u. At this site, 2.5% of the data points were above 1.05Vp.u. indicating the curve deployed in Phase 1 was not able to manage voltage to Rule 2 limits. It is likely that the curve assisted in maintaining an acceptable voltage, but more action was needed to definitively maintain Rule 2.

Phases 2 and 3 will explore this question further by testing different sets of Volt-Watt, Volt-VAR curves on the SIs, as well as collecting baseline data where no curve is running in order to better quantify the effect of the curve on voltage regulation.

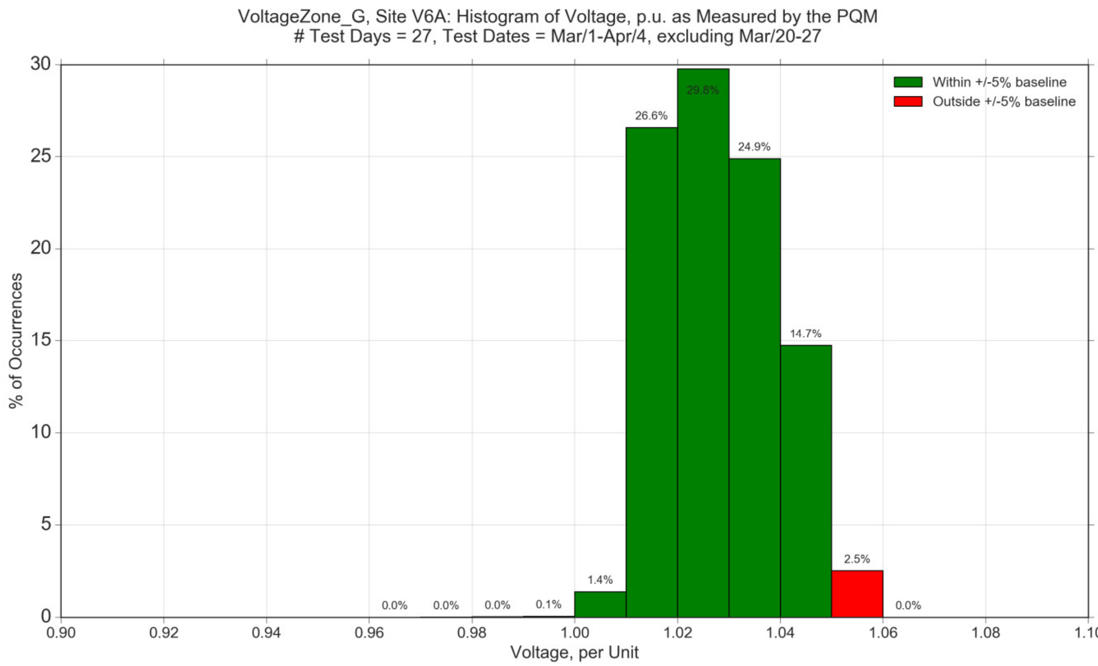


**Figure 4: Histogram showing percent of SI datapoints falling in "bins" of 0.01% Volts, per Unit as measured at the PCC**

## 3.4. SI Effect on Voltage at the Feeder Level

While this question was also not directly answered in Phase 1 as there was no baseline data with no curve settings running to compare against, the Phase 1 data could be again analyzed to understand the state of voltage on the feeder level and determine whether the curve settings were effective in managing them to effective values. Data for this analysis was gathered from SCADA devices, specifically distribution line reclosers reporting 3-phase voltage.

Figure 5 shows a histogram of the voltage data gathered at a feeder-level line recloser. The data shows that there were occasional instances where feeder voltage went outside +/-5% of nominal voltage during the Phase 1 period.

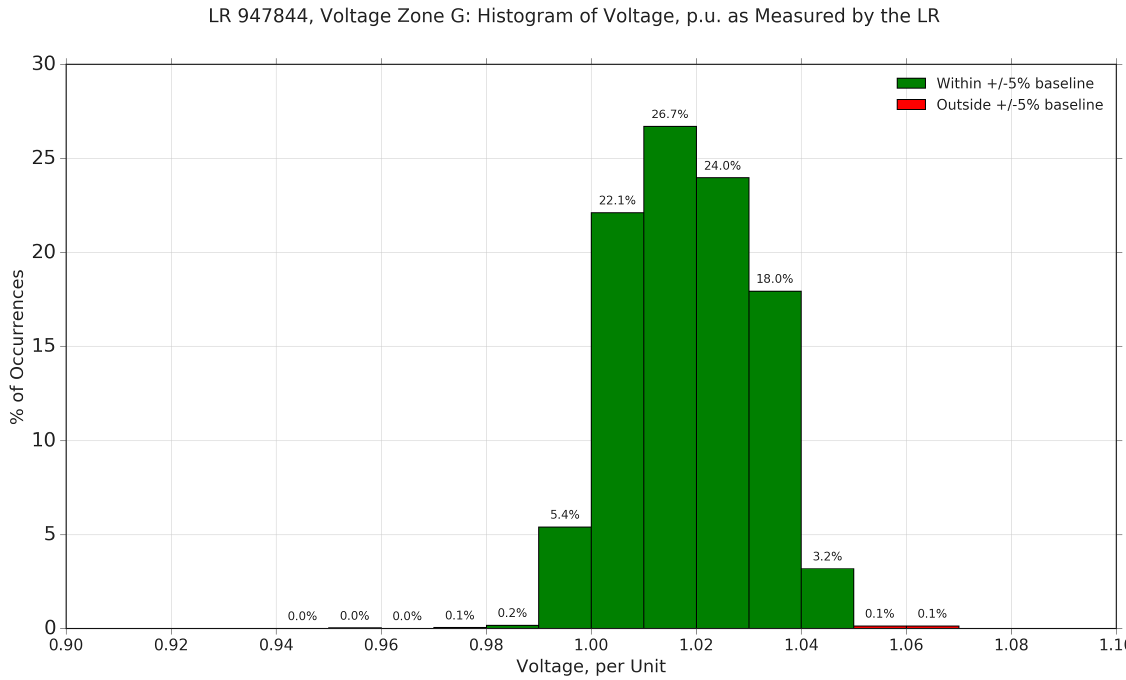


**Figure 5: Histogram showing percent of datapoints falling in "bins" of 0.01% Volts, per Unit as measured by the line recloser**

Phases 2 and 3 will explore this question further by testing different sets of Volt-Watt, Volt-VAR curves on the SIs, as well as collecting baseline data where no curve is running in order to better quantify the effect of the curve on feeder voltage. In addition, a parallel effort has been undertaken to analyze optimizing distribution line equipment to suit the voltage needs along the feeder based on load/generation composition at different nodes.

## 3.3. SI Effect on Customer Production

As each of the sites consisted of multiple inverters, a single inverter was selected to behave as a “baseline” inverter and was not set up to execute Volt-Watt/Volt-VAR curves. This was done to provide a baseline of expected active power production to compare against the production of the “active” inverters, which were following Volt-Watt/Volt-VAR curve settings. Curtailment was calculated at each of the pilot sites by comparing the total yield as measured by the active inverters to that of the baseline inverter. This was considered appropriate as the DC/AC ratios across all the inverters within the individual sites were constant.

The methodology made key assumptions. It assumed that the baseline and active SIs (and associated solar panels) were experiencing the same meteorological and environmental conditions. Specifically, that the SIs were housed in the same environment and they experienced the same operating conditions. It assumed that the solar panels experienced the same irradiance, temperature and wind values throughout the entire day. This is to say that there were no shadows that are cast on the panels, that they were co-located in the same wind streams, that they experienced the same ambient temperature throughout the day, and that the solar panel surfaces were equally efficient.

Using this methodology and assumptions, it was found that, on average across the field demonstration sites, the Volt-Watt/Volt-VAR curve set deployed resulted in 2% curtailment at the active SIs as compared to the witness inverter.

## 4. Practical Challenges

Several practical challenges were faced during the field demonstration.

- Manual retrieval of data from the sites was precluded by rains and muddy conditions at the customer sites
- Field-installed PQMs were needed as certain customer smart meters did not provide voltage data
- SCADA devices were incorrectly wired and did not provide valid insight into state of the primary
- Feeder-level activities e.g. reconductoring resulted in discontinuity in the test environment and needed to be carefully planned around
- Inverters were taken out of service due to failure. While this could be handled in data analysis, it required a robust framework to pivot quickly in analysis.
- Reactive power was not provided by the inverters and needed to be calculated in post-processing
- Inverters experienced issues in communications and firmware updates causing delays. Some inverters required individual firmware updates.
- The SI cluster controller periodically locked up and stopped recording data and had to be manually rebooted.

## 5. Future Work

The work presented here will continue through September 2018 in Phases 2 and 3 of the project. In these phases, five different combinations of Volt-Watt and Volt-VAR will be executed at the demonstration sites. In addition, “baseline” data will be gathered in order to observe the behavior without SI interaction.

In addition, Phase 3 involves the deployment of a web-based, vendor-agnostic aggregation platform that will allow remote setting of SI curves and retrieval of data. This will allow more frequent variation of curve sets (daily vs. weekly) as compared to Phases 2 and 3, along with higher frequency of data recording (2 minutes vs. 10 minutes).

## BIBLIOGRAPHY

[1] Pacific Gas & Electric Company "Electric Rule No. 2" Cal. P.U.C. Sheet No. 11896-E*