FINAL REPORT

Advanced Micro-Grid Energy Management Coupled with Integrated Volt/VAR Control for Improved Energy Efficiency, Energy Security, and Power Quality at DoD Installations

ESTCP Project EW-201147

OCTOBER 2016

Herman Wiegman
GE Global Research

Distribution Statement A
This document has been cleared for public release

Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)*
10-28-2016

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
2012 to Oct 2016

4. TITLE AND SUBTITLE

Advanced Micro-Grid Energy Management Coupled with Integrated Volt/VAR Control for Improved Energy Efficiency, Energy Security, and Power Quality at DoD Installations

5a. CONTRACT NUMBER
W912HQ-12-C-0002

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Herman Wiegman
Styliani Ioanna Kampezidou
Matthias Nikolakopulos

5d. PROJECT NUMBER
ESTCP EW-201147

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

GE Global Research
1 Research Cir
Niskayuna NY 12309

8. PERFORMING ORGANIZATION REPORT NUMBER

232524 – Final Report

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ESTCP
Energy & Water Program
4800 Mark Center Drive
Alexandria, VA 22305-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Available for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This demonstration program focused on methods to reduce peak electric power and electric energy consumption through Conservation Voltage Reduction (CVR) techniques. The first 2 years of efforts focused on advancing the IVVC technology. The later years of the project focused on building level voltage control, via Electronic Voltage Regulators (EVR's). The process of confirming peak power reductions and energy savings from voltage adjustments was tedious and resulted in less than expected savings. The building level voltage control equipment was not financially viable, and the alternative of manual adjustment of existing transformer tap settings was determined to be more cost effective than EVR technology. Additional observations about the migration of most electrical loads toward constant power characteristics also erodes savings potentials.

15. SUBJECT TERMS
Conservation Voltage Reduction, Energy Conservation, Peak Power Reduction, Voltage Control

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Herman Wiegman
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)* 518-387-7527

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Page Intentionally Left Blank

Table of Contents

List of Figures iv
List of Tables vi
Acronyms & Units vii
Acknowledgements vii
1. Executive Summary 1
1.1 Objectives 1
1.2 Technology 1
1.3 Performance & Cost Assessment 1
2. INTRODUCTION 3
2.1 BACKGROUND 3
2.2 OBJECTIVE OF THE DEMONSTRATION 4
2.3 REGULATORY DRIVERS 4
3. TECHNOLOGY DESCRIPTION 5
3.1 TECHNOLOGY OVERVIEW 5
3.2 TECHNOLOGY DEVELOPMENT 12
3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY 13
4. PERFORMANCE OBJECTIVES 16
5. FACILITY/SITE DESCRIPTION 17
5.1 FACILITY/SITE LOCATION AND OPERATIONS 17
5.2 FACILITY/SITE CONDITIONS 19
6. TEST DESIGN 21
6.1 CONCEPTUAL TEST DESIGN 21
6.2 BASELINE CHARACTERIZATION 21
6.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS 28
6.4 OPERATIONAL TESTING 30
6.5 SAMPLING PROTOCOL 30
6.6 SAMPLING RESULTS 30
7. PERFORMANCE ASSESSMENT 33
7.1 PEAK POWER REDUCTION 33
7.2 ENERGY CONSUMPTION REDUCTION 35
7.3 Energy Losses due to Inefficiency 36
7.4 QUALITATIVE VOLTAGE IMPROVEMENTS 36
8. COST ASSESSMENT 37
8.1 COST MODEL 37
8.2 COST ANALYSIS AND COMPARISON 38
9. IMPLEMENTATION ISSUES 40
Below is a summary of implementation issues. 40
10. RESULTS & DISCUSSION 41
10.1 CVR Assessment Efforts 41
10.2 TRENDS IN ELECTRICAL LOADS 41

10.3 Distribution level voltage control & Trends 41
10.4 Practical steps for Reducing energy consumption 41
10.5 Audit of Twentynine Palms building loads.....42
11. REFERENCES 43
12. APPENDICES 45
12.1 SCHEMATICS 45
12.2 DATA RECODRING METER DEVICES.....46
12.3 B1588 Voltage Quality 48
12.4 ENERGY MODEL RESIDUAL ANALYSIS.....50
11.4 ENERGY MODEL PREDICTOR ANALYSIS: BOX PLOTS.....54

List of Figures

Figure 1 ZIP model representation for electrical loads from DOE report [7]..... 5
Figure 2 Lamp Type Power-Voltage Profiles from EPRI report [6] 6
Figure 3 Peak Load Reduction from CVR [10] 7
Figure 4 Unregulated, line-connected motor efficiency and current for different mechanical loads. [6] 7
Figure 5 Example electrical loads and their power and energy characteristics vs. applied voltage..... 9
Figure 6 Example of a feeder with 5 nodes and examples of voltage profile vs. distance with either capacitive injection or large power injection at end of line..... 10
Figure 7 Two examples where a building level EVR regulates the voltage, given two different MV distribution circuit conditions..... 11
Figure 8 Technical steps necessary for implementing microgrids at the community level. 14
Figure 9 Primary relationships used to characterize the CVR of a feeder; a) sensitivity of load to applied voltage for constant impedance, current and power loads, as well as a typical feeder load mix. b) energy conservation versus the portion of the loads with process energy controls. 15
Figure 10 Photo of equipment garages with rooftop solar installations at MCAGCC at Twentynine Palms, CA showing pole mounted 12.5kV AC distribution network. 17
Figure 11 Map of the MCAGCC at Twentynine Palms showing the location of the selected building, B1588. 18
Figure 12 Photo of the selected building at the MCAGCC at Twentynine Palms..... 19
Figure 13 Photo inside of the electrical room at building B1588, showing a 480-208V transformer mounted to the floor, and electric load panels mounted to the wall. 20
Figure 14 Load Mixture in units of kW for B1588. 23
Figure 15 Daily Average Energy with Temperature in B1588 23
Figure 16 Daily Average Energy with Humidity in B1588 24
Figure 17 Normalized Voltage vs. Normalized Daily Average Energy in B1588..... 24
Figure 18 Daily Normalized Average Energy over 89 days in 208V Circuit 26
Figure 19 Normalized Daily Average Energy over 89 days in 480V Circuit 27
Figure 20 Basic one-line diagram for the layout of the EVR in the building. 28
Figure 21 The EVR device installed in the building, and the meter panel display. 29
Figure 22 Installed Meters and Cellular Router for data retrieval. 29
Figure 23 The potentials in both circuits of the building over five months in 2016.. 31
Figure 24 EVR output voltage settings during the Load Characterization Experiments on June 22, 2016. 31
Figure 25 Temperature and Humidity historical data over the five months of 2016 experiments. 32
Figure 26 Plot of delta-power vs. delta-potential data points from the load characterization experiment..... 33
Figure 27 Plot of all power vs. potential sampled points over the 1-hour load characterization experiment showing a 480V circuit with CVR-power slope of

0.22, and a 208V circuit with a CVR-power slope of 0.7..... 34
Figure 28 Response of power over time due to a voltage rise applied to three types of resistive loads, showing the probable closed loop response with slow feedback loads within B1588. 35
Figure 29 EVR Losses vs. Building 1588 Consumed Power, revealing a 2.1% loss..... 36
Figure 30 Example one-line diagram detail for the inclusion of the EVR at B1588? 45
Figure 31 Typical electric power quality meter for measuring 3-phase circuits..... 47
Figure 32 Example voltage quality event recorded at a convenience outlet inside B1588 showing only a minor notch from a switched load. 48
Figure 33 Typical 3-phase line-neutral potentials, and neutral to ground, at output of 208V transformer over the course of several hours, showing +/- 1% variation probably due to droops from building loads (e.g. a resistive dryer load, or air handler). 48
Figure 34 Typical potential for B1588 at meter 1 over two days, showing +/- 1.5% variation and an average input of 1.01 per unit (485Vrms) and a probable effects from solar power injection into the feeder during the middle of day. 49
Figure 35 Measured potentials for B1588 at meter 3 (EVR output) over several days showing +/- 1.5% variation and an average of 0.95 per unit (456Vrms) and effects from the EVR tap changing several times over three days. 49
Figure 36 Fitted Values vs. 208V Model Residuals..... 51
Figure 37 Theoretical Standardized Residuals vs. 208V Model Standardized Residuals. 51
Figure 38 Fitted Values vs. 208V Model Standardized Residuals Square Root..... 52
Figure 39 Leverage vs. 208V Model Standardized Residuals 52
Figure 40 Fitted Values vs. 480V Model Residuals..... 52
Figure 41 Theoretical Standardized Residuals vs. 480V Model Standardized Residuals. 53
Figure 42 Fitted Values vs. 480V Model Standardized Residuals Square Root..... 53
Figure 43 Leverage vs. 480V Model Standardized Residuals 54
Figure 44 Day of Week vs. Daily Average Energy at 208V Circuit..... 55
Figure 45 Day of Week vs. Daily Average Energy at 480V Circuit..... 55
Figure 46 Day of Month vs. Daily Average Energy at 208V Circuit 56
Figure 47 Day of Month vs. Daily Average Energy at 480V Circuit 56
Figure 48 Month of year vs. Daily Average Energy at 208V Circuit 57
Figure 49 Month of year vs. Daily Average Energy at 480V Circuit 57

List of Tables

Table 1 Example loads and their Power and Energy characteristics vs. applied voltage. ... 8
Table 2 Example feeder voltage profile cases. ... 9
Table 3 Comparison of various voltage level technologies ... 15
Table 4 Performance Objectives ... 16
Table 5 208V Circuit Model Coefficients and Error Performance for normalized model predictors from Equation (6). ... 25
Table 6 208V Model Coefficients Significance based on standardized model predictors 25
Table 7 480V Circuit Model Coefficients and Error Performance for normalized model predictors from Equation (7). ... 25
Table 8 480V Model Coefficients Significance based on standardized model predictors 25
Table 9 Available Measurements from B1588 after the installation of EVR ... 30
Table 10 CVR Power factors for B1588 by two estimation methods. ... 34
Table 11 CVR Energy factor for B1588 (from normalized data) ... 35
Table 12 Cost model for adding an EVR to a brownfield site ... 37
Table 13 Two configuration options for achieving voltage adjustment. ... 38
Table 14 Two configuration options with equipment and labor cost estimates. ... 38
Table 15 Simple Cost and Benefit assessment for two voltage setting strategies applied to a building with 75kW peak power consumption. ... 39
Table 16 Residuals at 208V Circuit ... 50
Table 17 Residuals at 480V Circuit ... 50
Table 18 Error Performance at 208V Circuit ... 50
Table 19 Error Performance at 480V Circuit ... 50

Acronyms & Units

CVR	Conservation Voltage Reduction, a reduction in peak load and energy consumption with reduced voltages based upon the load type
DETC	De-Energized Tap Changer, a transformer with a selectable tap that must be de-energized before changing
DoD	Department of Defense
EVR	Electronic Voltage Regulator, a solid state tap changing device which can regulate the output voltage to a set value
HV	High Voltage, transmission level circuits at >69 kV
IVVC	Integrated Volt/VAR Control, the control of several VAR sources based on their voltage measurements and knowledge of DER's in the feeder network
LTC	Load Tap Changer, a transformer with load sensitive tap position
MCAGCC	Marine Corps Air Ground Combat Center
MV	Medium Voltage, distribution circuits in the range of 1~ 69 kV
SCE	Sothern California Edison
SCR	Silicon Controlled Rectifier, used in AC circuits to commutate current
VA	Volt-Amp, units for apparent power
VAr or VAR	Volt-Amp Reactive, reactive power flow, either leading or lagging.
VVC	Volt/VAR Control, the control of a switched VAR source (typically a capacitor) based on local voltage measurements from the feeder.
W	Watts, units for real power

Acknowledgements

The authors want to recognize John Comparetto, Gary Morrissett, and Clovis Vaughn at the MCAGCC for their valuable inputs, guidance and access to their facilities.

The authors want to thank Nicholas Judson at MIT Lincoln Laboratories for his keen insights and technical acumen during the review and assessment of this body of work.

The authors thank Sumit Bose & David Wardwell at GE-Global Research for their support.

1. EXECUTIVE SUMMARY

This demonstration program focused on methods to reduce peak electric power and electric energy consumption through Conservation Voltage Reduction (CVR) techniques. Specifically, through the application of building voltage regulating equipment.

1.1 OBJECTIVES

The demonstration project had two main objectives:

- Reduce peak building power by >4% by reducing voltage from 1.0 to 0.95 per unit.
- Reduce daily energy consumption by >2% by reducing voltage from 1.0 to 0.95 per unit.

1.2 TECHNOLOGY

The initial project assessed two types of technology:

- Integrated Volt/VAr Control which optimally dispatches VAr sources (switched capacitors) and tap changing transformers to shape the feeder voltage profile for base-wide CVR savings.
- Building level electronic voltage regulator which regulates the building voltage level independent of the feeder input voltage, for building-wide CVR savings.

The first 2 years of efforts focused on advancing the IVVC technology which attempted to incorporate an electrical distribution model with known solar energy sources to shape the voltage profiles of the distribution feeders. This effort was terminated as the voltage profiles were not easily reduced with conventional, low cost switched capacitor banks on the distribution network, and the base did not control the settings of the feeder-head tap changing transformer.

The later years of the project focused instead on building level voltage control, via existing technology in the form of Electronic Voltage Regulators (EVR's), which was leveraged from an adjacent market (voltage support to buildings in poor power quality sites).

1.3 PERFORMANCE & COST ASSESSMENT

The net result from the demonstration of CVR at Building 1588 resulted in:

- peak load reduction of 1.9-5.6% which is within range of the goal of 4-5%.
- energy consumption reduction of 1.5%, which is less than the goal of 3-4%.

  Note: the voltage reduction is assumed to be set to 95% of rated.

Additional challenges and concerns to applying the technology are listed below.

- The above performances were only applicable to the target building, which had some significant resistive loads, such as electric laundry dryers, and an electrically heated sauna.
- The assessment of CVR impact and savings was very difficult, and required several months of data collection and non-trivial statistical analysis to determine the precise effect.
- The trend for electrical loads is toward constant power loads with closed loop controls. As a base adopts energy conservation measures, the benefits to CVR methods will erode.

The cost effectiveness of the demonstration of EVR technology was zero due to the additional losses in the EVR device eroding any peak power or energy savings benefit. An alternative method for achieving CVR through manual tap changes on existing transformers proves to be more cost effective (as manual tap changes only requires moderate amount of skilled labor applied once, assuming the feeder voltage profile is reasonably constant over time).

The benefit of CVR methods, at either the distribution feeder level or the building level, is eroding over time as loads become more electronically controlled and behave in a constant power and constant energy manner. Alternatively, energy efficiency efforts should first focus on updating loads which behave in a resistive, un-controlled manner (e.g. the electric laundry dryers with simple run time controller, should be displace with units that have “dryness” or humidity controlled turn off, or be updated with modern gas-fired dryers).

2. INTRODUCTION

The original project, as proposed by GE-Global Research in 2010, had an overall technical objective of implementing a centralized, campus-wide voltage management scheme which accounted for distributed energy resources (such as combined heat & power, as well as solar power) in order to provide Conservation Voltage Reduction (CVR) benefits and ensure voltage quality compliance. The original objective as proposed is shown below: [1]

> EW-201147: The objective of this project is to enhance and demonstrate advanced microgrid distribution management control technologies (including Integrated Volt/VAR Control (IVVC)) at Twentynine Palms, California. These technologies will help improve energy efficiency, increase energy security, and improve power quality at Department of Defense (DoD) installations.

The operational conditions at the target base, the MCAGCC at Twentynine Palms, changed over the time frame of the project as the base upgraded its electrical connection to the local utility, Southern California Edison (SCE). With this improved electrical connection, the voltage profile and power quality at the base improved. This resulted in voltage profiles that fell within specification and not in need of boosting to meet minimum quality levels. The IVVC methodology was based upon the use of switched capacitor banks at various locations within the network to help boost low voltage portions of the network, and shape a voltage profile that was close to the minimum allowed value for best CVR. The new infrastructure, in combination with the fact that the Load Tap Changer (LTC) at the key substations were not controlled by the base, but were seasonally changed by SCE, reduced the feasibility of the proposed IVVC strategy.

Due to the difficulty of showing benefit at the base level, the team pivoted and chose to demonstrate a different technology, which would have measurable benefit at the building load level, rather than at the feeder level. This building level voltage control device could impact the CVR of the building, independent of the feeder voltage level (whether it was too high or too low).

2.1 BACKGROUND

The intent of this demonstration is to evaluate the peak electric power reduction and electric energy consumption reduction effects from building level voltage control devices. The impact on building operations is expected to be minimal as these building level voltage control devices generally give consistent quality voltage, but at any programmable level between the ANSI suggested values. Also the voltage control devices have a by-pass switch that can disable them and return the building to normal operations. Current practices at military bases do not often tackle the issue of either distribution feeder level or building level voltage control.

Several options exist that attempt to shape the voltage profile along distribution feeders, but these primarily use reactive power injection methods. Updated methodologies that also account for the voltage effects from distributed energy resources (such as solar power) have also been developed, but require more control elements and a centralized control scheme to manage the new issues. This demonstration focuses instead on a robust building level voltage control scheme which uses a

[1] EW 201147 Fact Sheet from the ESTCP website: https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Microgrids-and-Storage/EW-201147

multi-tapped transformer to achieve accurate voltage control without reactive power manipulation.

This document will also include additional items to enhance the basic demonstration which include; trends in the nature of electrical loads, typical DoD installation electrical load characteristics, and the overall effectiveness of voltage conservation methods.

2.2 OBJECTIVE OF THE DEMONSTRATION

The project's objective is to assess the impact and cost benefit of building level voltage control devices on both the peak electric power and energy consumption. The technology that was studied in detail was an Electronic Voltage Regulator (EVR), which is a transformer-based device with multiple taps that are electronically controlled with silicon-controlled rectifiers.

The ESTCP has overall objectives of implementing energy conservation and efficiency technologies, and encouraging more distributed energy resources (such as solar power). To meet these overall goals, the project has pivoted from distribution feeder voltage management strategies to demonstrating technologies which are more easily applied across DoD installations.

The modified project objectives are:

- Implement building level voltage regulation equipment in order to demonstrate conservation voltage reduction (CVR) techniques.[2] The overall energy consumption reduction for the building load is expected to be on the order of 3~4%, depending upon the original voltage conditions which can have daily and seasonal variations. Note: this building level CVR objective will be met even with the presence of local solar energy injection which causes local feeder voltage rise.
- Implement building level voltage regulating equipment to demonstrate transient voltage support for sensitive loads. The technique is expected to prevent power quality issues and will enable sensitive loads or distributed energy sources to continue operation even in the presence of disturbances. The measurable impact will be voltage profiles that stay within +/-5% regulation bands for prescribed durations.[3]

2.3 REGULATORY DRIVERS

The primary DoD directive, which motivated this study, was the ESTCP focus on energy consumption reduction and reduced energy costs for DoD installations.

[2] PNNL 19596, July 2010 http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19596.pdf

[3] R. Comfort , A. Mansoor and A. Sundaram "Power quality impact of distributed generation: effect on steady state voltage regulation", *PQA 2001 North America Conf.,* 2001 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.202.5283&rep=rep1&type=pdf

3. TECHNOLOGY DESCRIPTION

This section of the report describes the underlying theory behind Conservation Voltage Reduction, and how it can be achieved at military bases.

3.1 TECHNOLOGY OVERVIEW

CVR methods are based upon the characteristics of electrical loads and how they respond to voltage changes over time. This section gives the theory behind the method and how it can be applied at either the distribution feeder or building level.

3.1.1 ELECTRICAL LOAD MODELING

To define the effect of voltage changes on load consumption, the power system society categorizes load behavior according to their voltage response in the following classes: constant impedance (Z), constant current (I) and constant power (P). Since some loads might preserve more than one of the following properties, a load can be fully characterized by the combination of all the previous three. The figure below represents a ZIP model. Equation (1) explains the effect of each load component in the power dissipation.

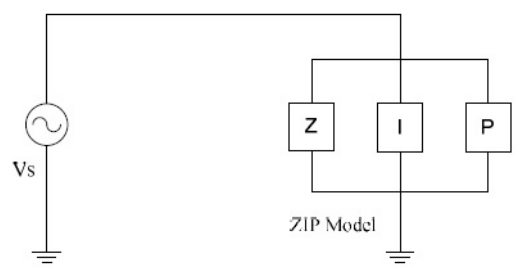


Figure 1 ZIP model representation for electrical loads from DOE report [7]

$$\frac{P}{P_o} = K_Z * (\frac{V}{V_o})^2 + K_I * \frac{V}{V_o} + K_P \quad (1)$$

$$K_Z\% + K_I\% + K_P\% = 1 \quad (2)$$

The following figures from EPRI's report [6], show lighting examples of an incandescence lamp which is a constant impedance load ($K_Z = 1,\ K_I = K_P = 0$) and a fluorescent lamp which is an almost constant power ($K_P = 1,\ K_I = K_Z = 0$) load.

Figure 2 Lamp Type Power-Voltage Profiles from EPRI report [6]

3.1.2 CONSERVATION VOLTAGE REDUCTION

The term Conservation Voltage Reduction (CVR) is normally applied to the energy savings aspects of reducing the voltage applied to loads, but can also be used to describe the peak power reductions from reduced voltages. The below sections describe these two sub-objectives.

Definition: According to the definition provided by the Department of Energy [7], Conservation Voltage Reduction (CVR) is a reduction of energy consumption resulting from a reduction of feeder voltage.

The earliest CVR was performed by the American Electric Power System (AEP) in 1973. The objective is to achieve energy savings (and therefore operational cost reduction and CO_2 emissions reduction) due to the drop in the power consumed by the loads connected to that feeder, reduce peak demand or reduce losses while maintaining the lowest customer utilization voltage consistent with levels determined by regulatory agencies and standards-setting organizations [8], [9]. American National Standards Institute (ANSI) sets the range for voltages at the distribution secondary terminals at 120 Volts ± 5% which is translated into the range of 114 Volts-126 Volts [11]. CVR is based on the principle that the feeder can be operated on the lowest half of 114 Volts-120 Volts without causing any issues to the devices connected to the feeder [12].

The benefits of CVR depend on the load's Voltage Sensitivity Factor (VSF) because essentially the CVR is interpreted as the load sensitivity to voltage changes. To quantify the efficacy of CVR method, a different CVR factor is used for energy savings or peak power reduction.

3.1.2.1 PEAK POWER REDUCTION

In the case of peak load reduction, the CVR factor is defined as the ratio of percentage of power consumption reduction over the percentage in voltage reduction.

$$\boldsymbol{CVR_{power}} = \frac{\boldsymbol{\Delta P}\%}{\boldsymbol{\Delta V}\%} \tag{3}$$

For a ZIP load representation, the CVR can be defined explicitly from equation (1) as the VSF (Voltage Sensitivity Factor) and thus defined as the derivative of the ZIP model with respect to voltage:

$$\boldsymbol{VSF_{ZIP}} = \boldsymbol{CVR_{power}} \quad = \boldsymbol{K_Z} * \mathbf{2} + \boldsymbol{K_I} \tag{4}$$

The effects of CVR implementation on peak load reduction can be simplified and summarized in the figure below. The peak load is reduced after applying voltage reduction [10].

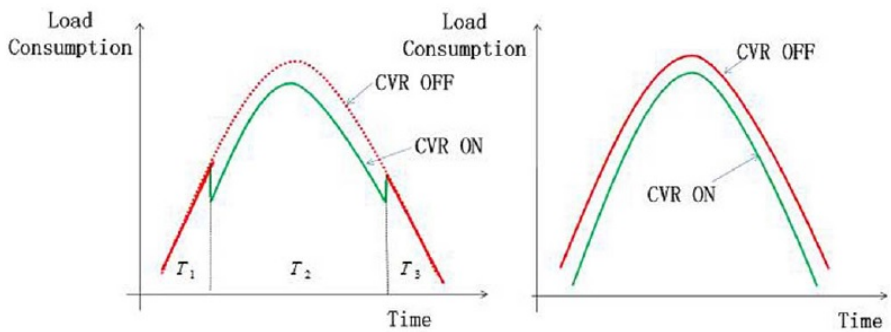


Figure 3 Peak Load Reduction from CVR [10]

EPRI has performed voltage change tests on different loads [14], [15], [6] in to order to quantify the power consumption as a function of voltage for those loads.

According to EPRI's study and experiments [10], both incandescent and fluorescent lamps tend to consume less energy at a reduced supply voltage which is a beneficial effect of CVR as well as increased lamp life due to reduced operating temperature as a consequence of reduced voltage [10], [16], [17]. On the other hand, high intensity discharge lamps may face reduced life duration when exposed to reduced voltage [4].
Electric motor load behavior with voltage reduction shows a different trend. More specifically, induction motors, which is the dominant motor type, show power consumption dependency with voltage level and motor loading. The unregulated motors (open-loop control, or line-connected) correlation of power and voltage depends on the motor type, size, load, speed etc. If the motor is operated at less than full load, which is very usual, then CVR methods can reduce the motor losses and increase efficiency, as mentioned in [10], [16] and [18]. To illustrate the potential savings from motor loads, EPRI provided an example of open-loop motor behavior to voltage reduction in [6] as shown in Figure 4.

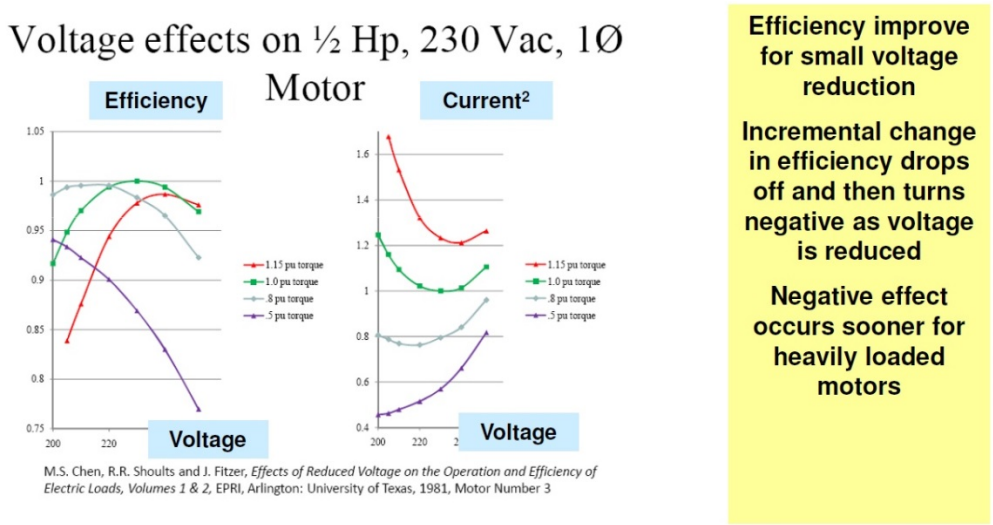


Figure 4 Unregulated, line-connected motor efficiency and current for different mechanical loads. [6]

3.1.2.2 ENERGY CONSUMPTION REDUCTION

The effect of voltage on energy consumption over the long term requires insight into the load's operation [7]. In the case of energy consumption reduction, the CVR factor is defined as the ratio of percentage energy change over percentage voltage change [10].

$$CVR_{energy} = \frac{\Delta E\%}{\Delta V\%} \tag{5}$$

Normally, one would expect constant impedance loads (resistive) to consume much less energy as voltage is reduced. However, this depends upon how the constant impedance load is operated over the course of the day.

Two forms of control which have opposite impacts on the energy consumption are; "constant time" controls, and "closed loop" controls. If the load is controlled with a simple timer or runs a fixed number of hour per day, then voltage level can impact the total energy consumption. If the load is controlled by a separate productivity parameter, such as temperature, light output, or other independent parameter, then the total energy consumed will **not** be a function of voltage.

Loads are categorized in the following way: **closed-loop** loads have a control mechanism which can changes the operation of the load to compensate for the input voltage variations while **open-loop** loads do not [10].

- "Open-loop loads are typically lightning loads (e.g. incandescent lamps, fluorescent lamps and high intensity discharge lamps) and unregulated motors (e.g. ventilation motor).
- Typical closed-loop loads are motor drives, thermal cycle loads (e.g. electric water heaters) and regulated constant power loads (such as furnaces)" [10].

Table 1 and Figure 5 below show three examples of loads with different ZIP characteristics, and control methods. The example shows how peak power and energy consumption results vary across these loads.

Table 1 Example loads and their Power and Energy characteristics vs. applied voltage.

Example Loads	Peak Power Characteristic	Energy Characteristic
a) incandescent operated 1 hour per day	scales with the square of voltage	scales with the square of voltage
b) electric water heater, regulating water temperature	scales with the square of voltage	constant (it is a function of water use, not voltage)
c) computer monitor, operating 5 hours per day.	constant (not a function of voltage)	constant (it is a function of operating hours per day)

Example Loads			
Load	Incandescent	Water Heater	Computer
Control	On/Off	Temperature	On/Off
Usage	Fixed time	Gallons per day	Fixed time
Peak Power	$P \propto V^2$	$P \propto V^2$	P constant
Energy Consumption	$E \propto V^2$	$E \propto$ usage	$E \propto$ usage

Figure 5 Example electrical loads and their power and energy characteristics vs. applied voltage.

3.1.3 ELECTRIC DISTRIBUTION FEEDER

Electric utility companies have considered leveraging the above information to help reduce overall peak power demand and energy use on distribution feeders through voltage reduction techniques. The general concept is to shape the voltage profile down the feeder so it is as low as possible, without violating voltage standards. The two tools available to distribution companies are the substation transformer tap settings at the "head" of the feeder, and reactive power injection devices down the feeder, typically in the form of switched capacitors to help boost low voltages.
The below Figure shows an example of a distribution feeder with 5 load nodes. The Figure also shows an example of three voltage profiles for three scenarios. These scenarios are explained in Table 2.

Table 2 Example feeder voltage profile cases.

Scenarios	Feeder head condition	Comment
Blue – baseline condition	Set to 1.02 per unit voltage under nominal loading	Typical feeder profile
Green – VAr injection at node 3	Set to 1.02 per unit voltage under nominal loading	Cap banks generally increases voltage locally
Red – PV injection at node 5	Set to 1.0 per unit voltage under light loading	PV injection can increase voltage locally.

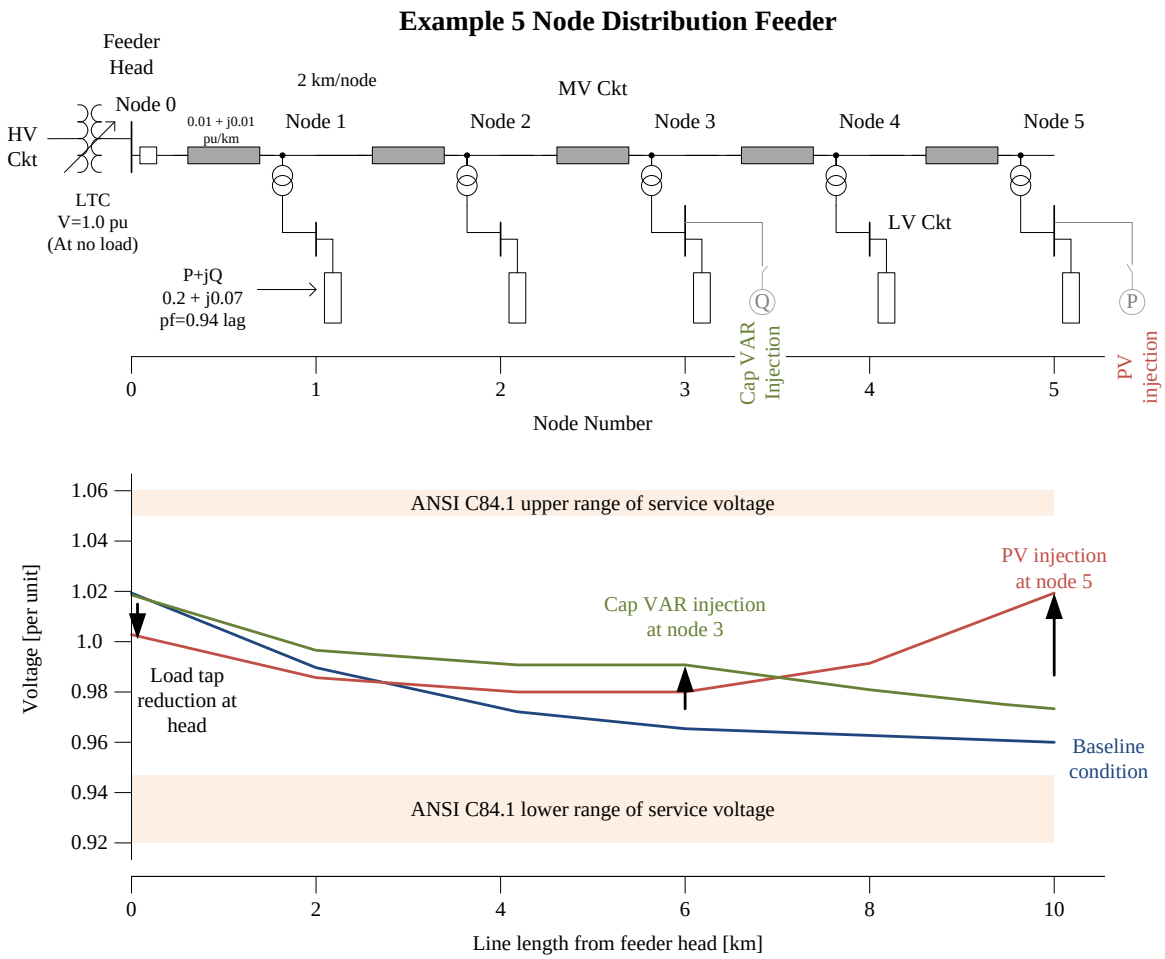


Figure 6 Example of a feeder with 5 nodes and examples of voltage profile vs. distance with either capacitive injection or large power injection at end of line.

Ideally, a distribution management system with Integrated Volt/VAr Control (IVCC) would set the feeder head tap changer setting in concert with capacitor bank dispatch signals and PV injection timing to produce a feeder voltage profile that was low as acceptably possible.

3.1.4 BUILDING LEVEL VOLTAGE CONTROL

Building level voltage control is performed with the assistance of electronic voltage regulator (EVR) technology. The EVR technology is able to regulate the RMS potential at the building level even when the distribution system voltage is varying, due to the electronically controlled taps which span a broad buck-boost range. The figure below shows two examples of voltage control on a building using EVR, in example #1 the EVR bucks the potential down to the ANSI limit, in example #2 the EVR boosts the potential of a deeply depressed feeder back to acceptable limits.

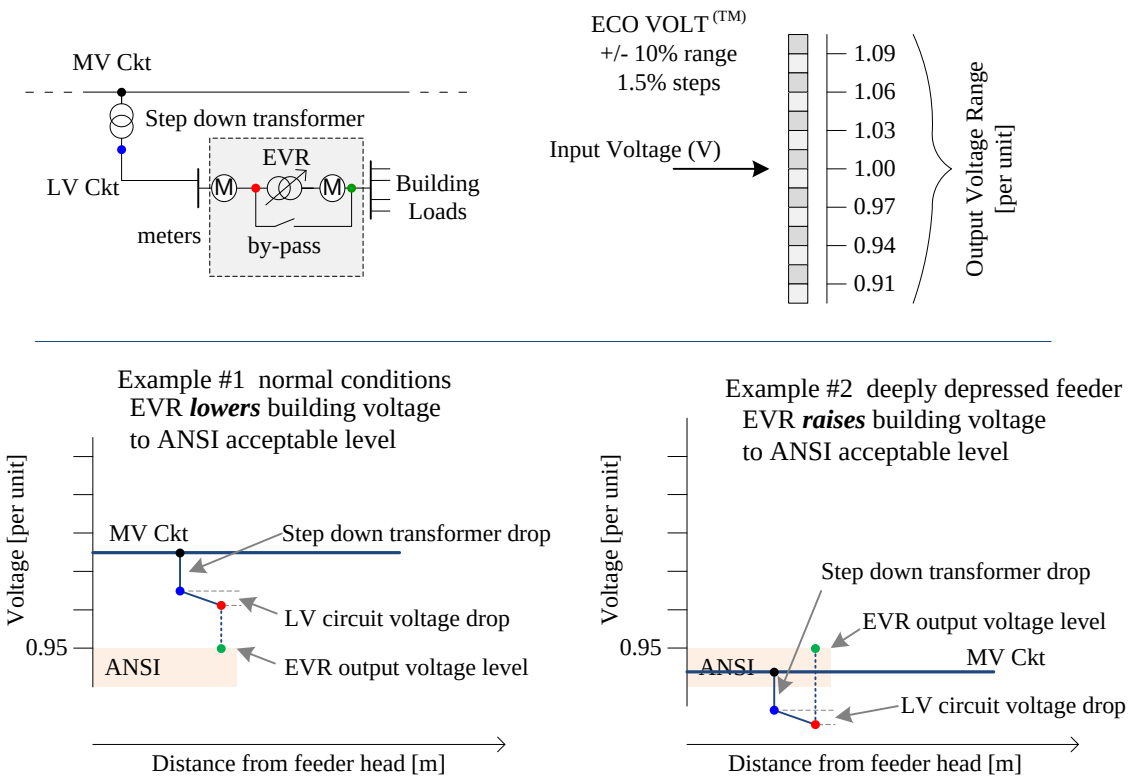


Figure 7 Two examples where a building level EVR regulates the voltage, given two different MV distribution circuit conditions.

Note: the examples in Figure 7 include a potential drop due to the leakage impedance of the MV to LV step down transformer. This potential drop can be as much as 5% for a fully loaded distribution transformer.

3.1.5 SUMMARY OF VOLTAGE CONTROL TECHNOLOGIES

Electrical distribution network equipment providers offer the following voltage control technologies for influencing or adjusting voltage levels:

- Volt/VAR Control (VVC) products which are applied to feeder level capacitive VAR compensation devices to help raise voltage at that particular location along the feeder. (As shown in Figure 6)
- Integrated Volt/VAR Control (IVVC) products which are applied to several feeder level capacitive VAR compensation devices to help shape the overall feeder voltage profile in a coordinated manner with known DER resources.
- Load Tap Changing Transformers (LTC) products which are applied at the feeder head or point of coupling to the transmission network. These devices set the feeder head voltage level as a function of feeder load and may change settings a few times per day as load varies. (As shown in Figure 6)

- Smart Inverter products which offer both capacitive and inductive VAR compensation based upon local voltage information or perturbations. This technology works well to adjust local voltage by a percentage point or two, but is not able to efficiently address large voltage adjustments. The standards that apply to this technology are not fully mature and require more definition before wide spread use.
- Building level Electronic Voltage Regulators (EVR) products which are similar to LTC's but with solid state switching devices that can continuously change the effective tap ratio of the device to provide near constant voltage to the building, independent of distribution feeder voltage. (As shown in Figure 7)

This project originally focused on IVVC methods applied to the distribution network of the base, and then pivoted to demonstrating building level EVR technology.

3.2 TECHNOLOGY DEVELOPMENT

The GE company was involved with three projects at the MCAGCC at Twentynine Palms.

3.2.1 FEEDER LEVEL TECHNOLOGY DEVELOPMENT

GE adopted a model-based Integrated Volt-VAr Control approach for the Twentynine Palms network. Central to this approach is an accurate representation of the electrical network using OpenDSS. The distribution power flow model consists of models to represent solar PV systems and voltage control devices such as voltage regulators and cap banks, in addition to branch and load transformer impedances and distributed generators. This model was used to run Quasi-Static Time Series simulations in order to simulate the different operating points for the network and to capture the effects of high PV penetration in certain feeders of the Twentynine Palms network. The model was validated using site SCADA measurements.

A dynamic programming-based optimization scheme was developed to determine the dispatch for the different voltage control devices with objectives such as voltage flattening, elimination of voltage violations, power factor correction and peak power reduction through conservation of voltage reduction (CVR). Given the strong electrical connection between the Twentynine Palms network and the utility in-feed, peak power reduction from CVR was considered as the best value proposition. Since the demonstration of such a scheme at feeder level would require the following:

- installation of costly Load Tap Changer (LTC) at the main substations feeding the base
- update of the network model on an annual basis due to base build-out and expansion
- update of the DER/PV sources in the model as they are added to the base

Subsequently a building-level CVR demonstration was selected which was a more affordable and tractable project.

3.2.2 BUILDING LEVEL TECHNOLOGY DEVELOPMENT

The GE team pivoted the project to building level voltage control devices, and leveraged the existing designs from a US based manufacturer. These EVR's were traditionally used in US embassies and buildings in foreign lands where there is poor electrical quality. No special technology development was needed to adapt the EVR to the application of peak power and energy

conservation. Instead, the project focused on the applicability of this technology to meeting ESTCP goals.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The project originally intended to demonstrate medium voltage feeder control of VAR injection and tap changer control to optimize the feeder voltage profile for power quality and energy conservation reasons. These techniques were originally planned to be integrated with a centralized microgrid/network controller that could communicate with the various feeders and VAR injection assets (switched capacitors). Due to changes in the electrical infrastructure at the target base during the period of performance, the original proposed solution lost many of its potential benefits and the relative cost to implement was no longer attractive. Additionally, the base did not control the tap changing transformer which fed the base and could not coordinate the voltage tap with voltage boosting capacitors in the base's distribution network, thus making feeder voltage profile shaping and CVR unobtainable.

3.3.1 DOD TECHNOLOGIES

The voltage regulating equipment at military bases is often limited or non-existent. The demonstration base, MCAGCC at Twentynine Palms, has minimal capacitive VAR injection elements in the distribution feeder network on the property and it has no voltage regulation equipment such as feeder load tap changing transformers. Rather the base only has conventional building level and residential transformers that may feature de-energized tap changing (DETC) switches.

The target base does operate bulk power factor correction capacitors at the main substation, but these do not address the issue of poor feeder voltage profiles. The local utility owns and operates the HV to MV step down transformer at the point of interconnect, and the utility controls the tap setting. It is assumed that many DoD bases have similar situations, thus have limited CVR opportunities at the feeder level.

This study migrated to a demonstration of building level voltage control devices which are readily available and can be installed in a piecemeal or prioritized fashion, where deemed most effective.

3.3.1.1 MICROGRIDS

The DoD is actively investigating microgrids for their bases, which address issues such as energy security and resiliency to electric utility events, and natural disasters. Microgrids may not specifically address CVR efforts, but microgrids do incorporate controls, communication and a network control center which can help manage CVR elements if adopted.

An example process to assess, prepare and mature a microgrid at a DoD installation is shown in Figure 8. The process to mature microgrids highlights several key hierarchical categories that need to adopt certain key functions. Each DoD installation may have different aspects of the process covered and may need to apply effort in different areas to mature their microgrid capability and maturity.

It is also important to consider the organizational commitment and staffing necessary to implement a multi-year process to achieve the goals for microgrid efforts. This usually takes a skilled facility manager who has access to local 3rd party engineering firms who can help implement the aspects of Figure 8.

The MCAGCC at Twentynine Palms has been simultaneously experiencing facility growth and expanding its microgrid's capability to include more of the key loads so they can survive loss of electrical feed (and natural gas feed).

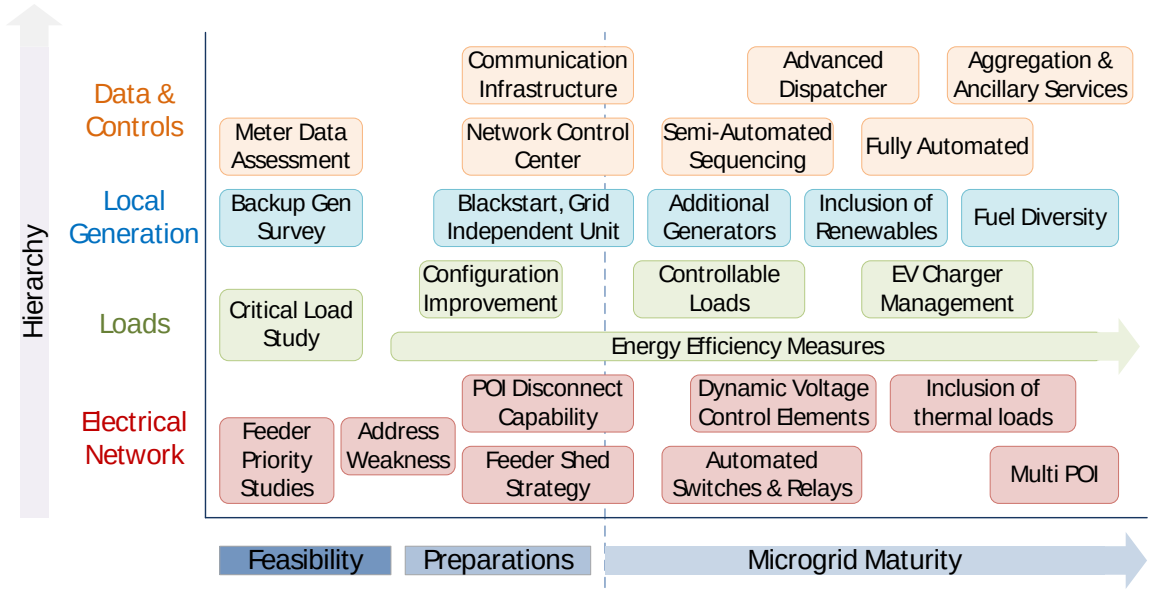


Figure 8 Technical steps necessary for implementing microgrids at the community level.

3.3.2 OPPORTUNITY FOR BUILDING LEVEL VOLTAGE CONTROL

The peak power and energy conservation opportunities for EVR technology was originally estimated to be approximately 3~4% reduction in a building's energy consumption and a 4~5% reduction in its peak load demand, assuming a 5% voltage drop from nominal conditions was tolerable. These predictions were based on a typical load mix and a typical proportion of loads that have closed loop control (temperature or process controls). These projections are better than has been reported by previous studies that have implemented CVR techniques at the feeder level, such as the Boise Idaho Study that documents results from a 3% voltage drop experiment, which resulted in 1.8 ~ 2.6% peak load reduction, and a 1.5~2.5% energy consumption reduction.[4] The main difference between building level and feeder level control is the ability to accurately drop the voltage at the load to a programmable level. The feeder voltage profile is often non-optimal for several of the locations, while building level voltage control can precisely set the voltage to a lowest allowable value. See Figure 9 for more details.

[4] Conservation Voltage Reduction, Phillip Anderson, Idaho Power, 2013
https://www.idahopower.com/pdfs/AboutUs/PlanningForFuture/irp/2013/DecMtgMaterials/ConservatioVoltageReduction.pdf

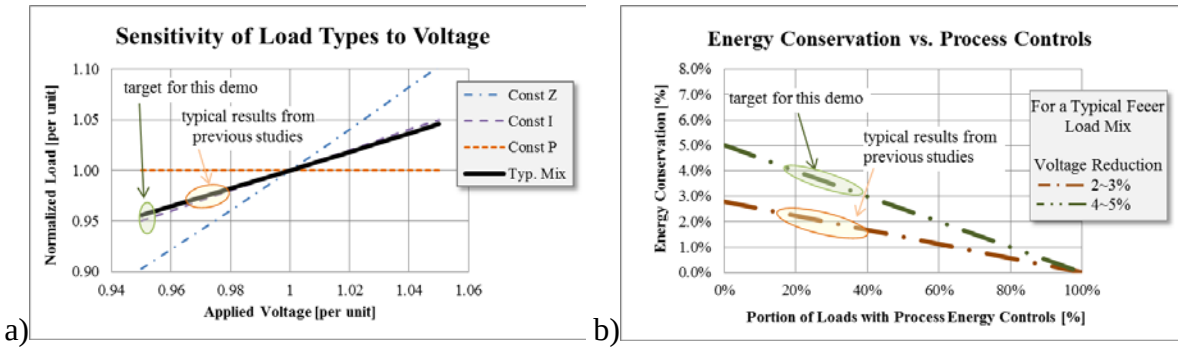


Figure 9 Primary relationships used to characterize the CVR of a feeder; a) sensitivity of load to applied voltage for constant impedance, current and power loads, as well as a typical feeder load mix. b) energy conservation versus the portion of the loads with process energy controls.

There are several available technologies available to influence or set voltage levels on distribution feeders and at the building load level. Below is a listing of the considered technologies and their relative merits.

Table 3 Comparison of various voltage level technologies

Technology	Main advantage	Main Disadvantage	Cost ($/kVA) [5]
Load Tap Changing Transformer	efficiently changes the voltage at the head of a feeder as a function of feeder load	does not account for DER's or VAR sources down the feeder. moderately expensive technology	100-200
Switched Capacitor Banks with local control	can economically raise local feeder voltage when droop becomes an issue (near end of line).	does not address non-local voltage issues, limited switching events per day. can only raise voltages.	50-60
Centralized Control of Switched Capacitor Banks	can optimize voltage profile based on knowledge of feeder and DER's	requires data and communications, more expensive than local control, can only raise voltages	80-100
Building Level VAR injection (Smart inverters)	can dynamically inject +/- VARs to smooth or adjust building level voltage. may be integrated into future solar inverters	can force large power factor changes at building level. expensive if not integrated with other functions (solar inverter)	200-300*
Building Level Tap Changer (EVR)	can accurately regulate voltage at the building loads	no ability to impact feeder voltage (only load side), moderately expensive	150-200

[5] Capacitor Application Issues, Eaton Corporation, Thomas Bloomberg, Daniel Carnovale, whitepaper on www.eaton.com
* the cost of smart inverters can be associated with the primary function, like solar power, so no additional cost for VAr injection

4. PERFORMANCE OBJECTIVES

The performance objectives are summarized in the table below.

Table 4 Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Reduce peak power	peak electric power consumed on a daily basis	Electric meter data over several months	4-5% reduction in peak power
Reduce energy consumption	electric energy consumed on a daily or monthly basis	Electric meter data over several months	3-4% reduction in energy consumption
Qualitative Performance Objectives			
Fewer voltage related issues	number of complaints or documented issues at building level	feedback from staff and reported incidents of equipment operation	no reported issues due to voltage quality

The performance objective for the demonstration equipment is the overall reduction of electrical energy use in the target building and a reduction in the peak load demand, as well as the improved robustness of the building loads to electrical feeder voltage disturbances. The demonstration will quantify the above benefits and evaluate cost to derive a cost/benefit analysis and payback period.

4.1.1 OPTIONAL QUANTITATIVE PERFORMANCE OBJECTIVES

The quantification of the scalability of the proposed technology across all of DoD's installation may be attempted by surveying the MCAGCC facility. The target base is representative of other military installations and the diversity of the buildings may prove to be a good sampling of what can be expected at other locations.

The stability of the demonstration design (or the availability of equipment options) to variations in the electrical systems of various buildings will be considered and documented as part of the final report.

4.1.2 OPTIONAL QUALITATIVE PERFORMANCE OBJECTIVES

The demonstration project may choose to evaluate the robustness of sensitive loads to feeder voltage disturbances in a qualitative manner, due to various limitations in precisely measuring load sensitivity to voltage disturbances.

5. FACILITY/SITE DESCRIPTION

The MCAGCC at Twentynine Palms has been an aggressive adopter of renewable energy and is located 120 miles East of Los Angeles, CA. The base boasts more than 8MW of solar power, >30MW of total load, and >10 MW of natural gas fired co-generation. The recently updated electrical feed from Southern California Edison now gives the base a redundant electrical feed and a reliable source of power.

Figure 10 Photo of equipment garages with rooftop solar installations at MCAGCC at Twentynine Palms, CA showing pole mounted 12.5kV AC distribution network.

5.1 FACILITY/SITE LOCATION AND OPERATIONS

The demonstration site is located in the Mojave desert area in South Eastern California and the buildings have a significant chiller load to condition the living and working spaces within the them. These chiller loads generally do not have a significant CVR factor (energy reduction from voltage reductions), but other loads within the buildings may have CVR factors.

The primary selection criteria for the demonstration are listed below. The ideal building would be one that has all of the below criteria to maximize the benefit and effectiveness of the demonstration.

- A building that has known issues with voltage quality due to large motor starting loads, or solar power variability, or sensitive building loads.
- A building with a reasonable mix of loads which will result in energy use reductions from voltage level reductions. (note: constant power loads have the least sensitivity to voltage variations, while motor and lighting loads present more CVR savings).
- A building with accessible electrical service which will easily allow the installation of the EVR.
- A building with non-critical load that does not directly serve an active mission of the base.
- A building with a reasonable demand load, and an electrical service and infrastructure that lends itself to a comprehensive analysis of the entire facility.

The selected location of the EVR demonstration will be at building B1588 (East Gymnasium)-

which satisfies the majority of the above requirements:

- This building experiences voltage variation, harmonics, and P.F. issues (0.1 on CØ).
- The building contains a mixture of load types, and also both 480/277 and 208/120 voltages – which can be separately adjusted.
- It is fed by a 225kVA pad-mount transformer located outside, just east of the Electrical Room – which does have the requisite space for the EVR to be located indoors.
- As one of (2) gymnasium facilities located within a half-mile of each other, the load is not only non-critical, but also the facility does have some redundancy.
- The ongoing demand load should be sufficient to generate quantifiable savings – especially as it is a newly operated 24-hour facility.

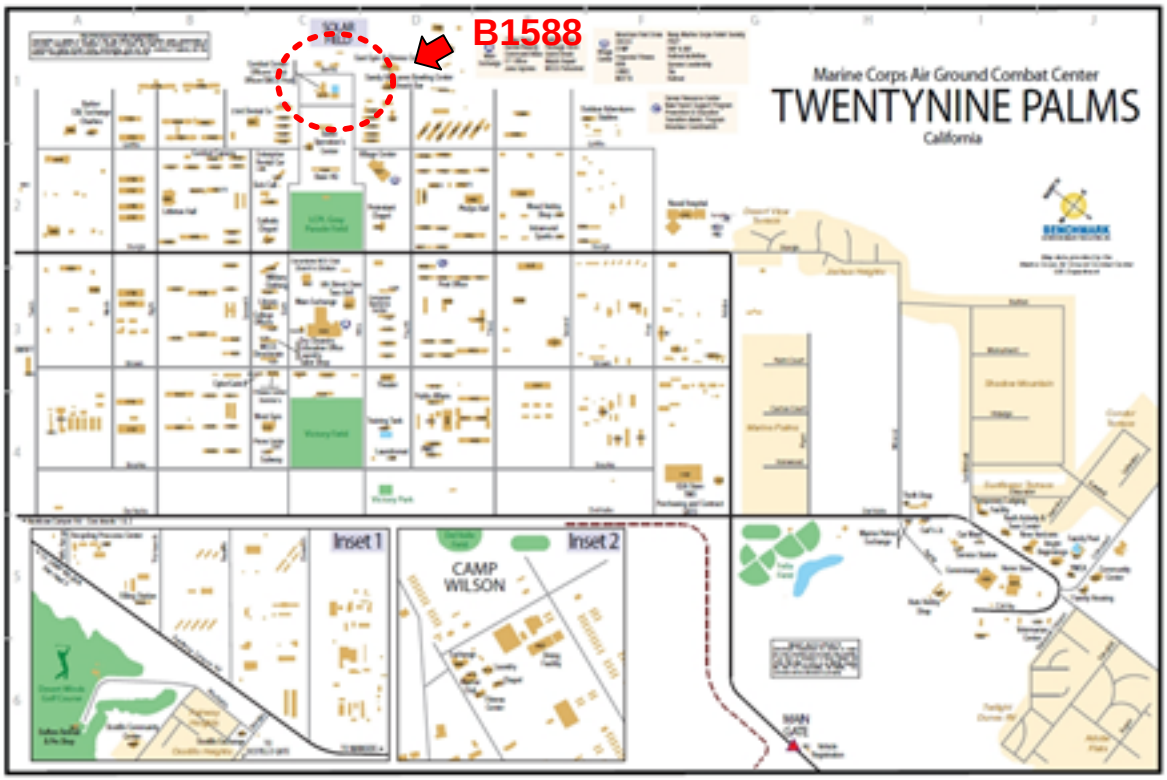


Figure 11 Map of the MCAGCC at Twentynine Palms showing the location of the selected building, B1588.

Figure 12 Photo of the selected building at the MCAGCC at Twentynine Palms.

5.2 FACILITY/SITE CONDITIONS

The selected building, B1588 has the following function: East Gym & Fitness Center

- ~30-yr. old 22,300 SF single-story CMU building - located at the far east end of 4th Street, approximately in the middle of Mainside. Added on to under project P641.
- As B1588 is located at the dead end of 4th Street, there are no key military operations occurring near the site. EVR monitoring and demonstration should have no impact.
- Building managerial personnel are fully aware of the operation, and very cooperative: easy, willing, and able to accommodate the installation and demonstration - as need be.
- An important advantage of this candidate building was the fact that it had space within its Elec. Rm. (albeit w/ some re-configuration) to allow the AVR to be installed indoors: critical in this environment - due to the extreme heat, and sandy conditions, outdoors.
- This also allowed for metering, tap-changing, and AVR setting to take place in a relatively clean and controlled environment, and within close proximity to each other.
- Unfortunately, the Elec. Rm. doubles as the Mech. Rm., and the AVR is relatively large (barely fitting through the door), but adequate space was created to accommodate it properly, still maintaining proper clearances to all equipment, and secure the cellular router.
- Although the Elec. Rm. can get relatively warm inside, a ½ HP exhaust fan maintains indoor air temperature to below ±100°F. (indoor air temp is monitored in 24-hr. cycles).
- Existing Swbd. wireway facilitated connecting the AVR feeders to the incoming section.

The selected buildings do not have any key military operations taking place in them.

Figure 13 Photo inside of the electrical room at building B1588, showing a 480-208V transformer mounted to the floor, and electric load panels mounted to the wall.

5.2.1 SITE-RELATED PERMITS AND REGULATIONS

No special permits are needed for the planned equipment installations at the above facilities to achieve the testing objectives. The equipment will be installed at the Low Voltage side of building electrical service which will not impact utility interconnect agreements.

There are no special regulations governing the testing procedures and objectives besides normative electrical installation regulations and safety oriented electrical equipment operations.

5.2.2 PROPERTY TRANSFER OR DECOMMISSIONING

The equipment that will be installed on the base will be UL certified and be supported by manufacturer's warrantees. The equipment will also feature "by-pass" features in order to support "before and after" testing. Due to these attributes the equipment, if successful, can be left on base at the conclusion of the project.

Property Transfer from ESTCP to the MCAGCC is possible and a release of liability for the equipment is being considered and formulated.

6. TEST DESIGN

6.1 CONCEPTUAL TEST DESIGN

The basic concept of the test plan is based upon two types of experiments: one which quickly measures the changes in power consumption with step changes in voltage, the second which observes many days of energy consumption at each voltage setting.

6.1.1 PEAK POWER REDUCTION EXPERMENTS

These experiments involved changing the EVR output setting several times over the course of an hour. During each step change in EVR voltage output, the power consumption was recorded (1-min averages) and assessed for a similar step change.

These experiments were applied twice, once in January and once in June in order to capture a broad range of ambient temperatures.

Noise factors included loads within the building which happened to switch on or off during the 1-minute averaging of power.

Note: data from two separate meters was used to differentiate the 480V and 208V circuits within the building.

6.1.2 ENERGY CONSUMPTION REDUCTION EXPERMENTS

These experiments involved changing the EVR output setting several times over the course of months. During each step change in EVR voltage output, the daily average energy consumption was recorded and assessed for a step change.

Secondary factors included environmental and weather data from NOAA over the time period of interest. The testing was scheduled over a time period from January to June to cover a broad range of ambient temperatures.

Noise factors included human occupancy rates, building equipment breakdowns, holidays, and transfer of laundry services from one gym to another based on equipment failures.

Note: data from three separate meters was used to differentiate the 480V and 208V circuits within the building, and the inefficiency of the EVR itself.

6.2 BASELINE CHARACTERIZATION

6.2.1 PEAK POWER REDUCTION EXPERMENTS

These experiments do not require any baseline data or modeling. Rather, after the data is collected, the voltage and power response data can be normalized to nominal or average values so that just the sensitivity of power is evaluated against changes in applied voltage.

6.2.2 ENERGY CONSUMPTION REDUCTION EXPERMENTS

These experiments do not require any baseline data or modeling before the application of the EVR. Rather, the experimental data is correlated with the primary and secondary factors using statistical tools. So the primary effect of CVR can be extracted without a baseline model for the building.

Early efforts to characterize the target building (B1588) focused on modeling the hourly power

consumption behavior. These efforts were abandoned after there was difficulty in differentiating the daily power variation with various factors such as daily temperature swings, and daily voltage variation. These factors were often negatively correlated and were confounded in the analysis.
Later efforts by the team focused on the characterization of B1588's daily average energy consumption as a function of several factors. These factors included; daily average RMS voltage, daily average ambient temperature, daily average humidity. The energy consumption tests were applied over a period of 89 days from January 28th until April 7th and from June 8th to June 19nd, 2016.

6.2.3 DISTRIBUTION FEEDER VOTLAGE VARIATION

To better serve the purpose of energy CVR factor estimation, the proposed energy model uses daily average values of temperature, humidity and voltage for the 208V and 480V circuits separately. The concept behind using a daily average energy model is that the average voltages on the two building circuits over a day are direct indications of the energy consumption related to CVR effects other than line voltage noise due to events upstream in the feeder. After applying CVR on the building, the average level of voltage changes mostly due to the CVR effect (+/-5% variation) and almost not at all by the line noise (<1% variation). This assumption is based on the fact that the line noise is random and cannot be modeled, thus it is assumed constant and independent of the CVR effect over the course of the day. Thus, the daily average voltage noise is incorporated in our regression model in the constant coefficient β_0 along with other factors that have an overall constant effect on energy consumption over a day for all the 89 days tested and are not correlated with the day of the year, weather or CVR. These factors are the average building consumption due to device operation, human occupancy and line voltage noise.

6.2.4 SEPARATION OF 480V AND 208V CIRCUITS

The two electrical circuits within B1588 are modeled independently. This differentiation was important as the 480V circuit was found to be more affected by the weather conditions (temperature and humidity) than the 208V circuit due to the building's cooling and heating systems being connected to the 480V circuit. On the other hand, the 208V circuit energy consumption was found to be more correlated with voltage and voltage squared than with weather conditions. This is due to the exercise equipment and laundry services (resistive loads) being connected to the 208V circuits. The building's load distribution is shown in Figure 14.

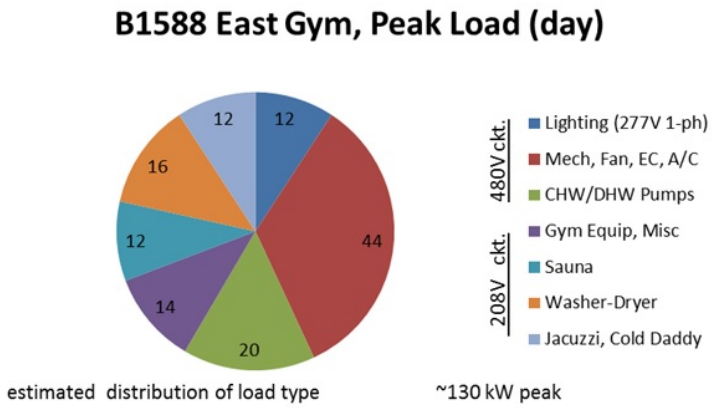


Figure 14 Load Mixture in units of kW for B1588.

It is worth mentioning that Protocol #1 is a recommended procedure to calculate energy savings using the definition in (5) either for loads [19] or for feeders [20]. However, in the case of our specific experimental configuration, the resultant model was different due to a very diverse mix of loads on both circuits and also due to the observed correlation between the different factors and the energy consumption.

First, the analysis observed a different correlation between daily average energy and daily average temperature in the two circuits. The 208V circuit daily average energy seems to have no correlation with daily average temperature but the 480V does as shown in the figure below. This is explained by observing that the 480V circuit contains cooling-heating units which are closed-loop loads around temperature. The cooling/heating effect of the air-conditioning devices can be affected by the relative humidity in the air and thus it is important to include daily average humidity in the model.

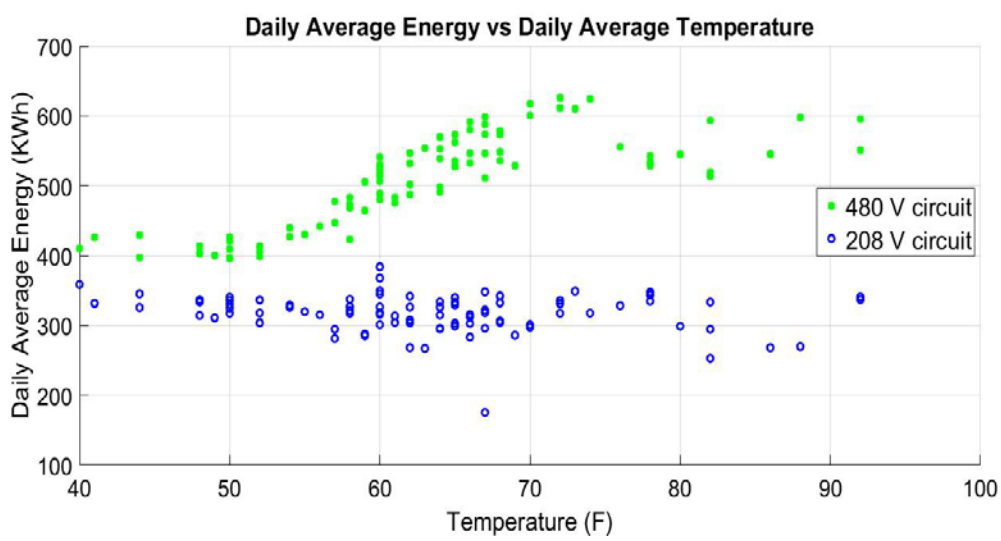


Figure 15 Daily Average Energy with Temperature in B1588

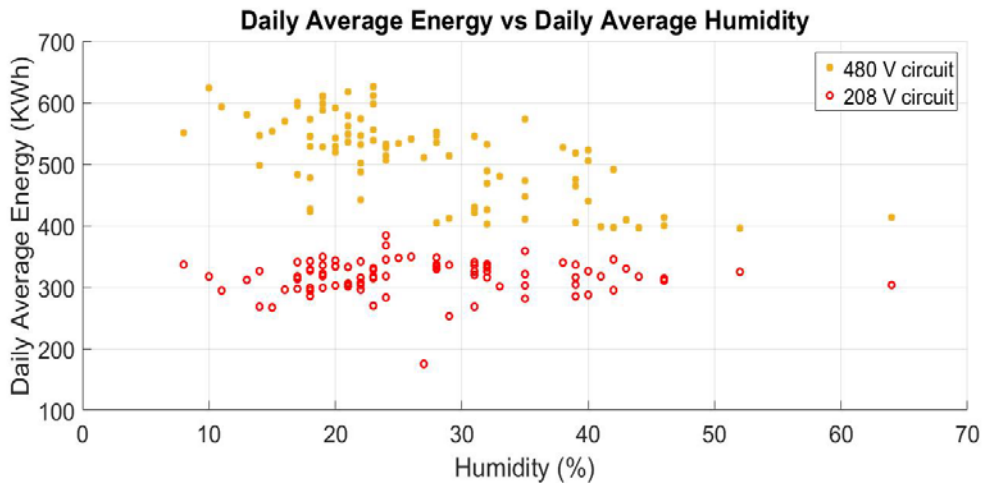


Figure 16 Daily Average Energy with Humidity in B1588

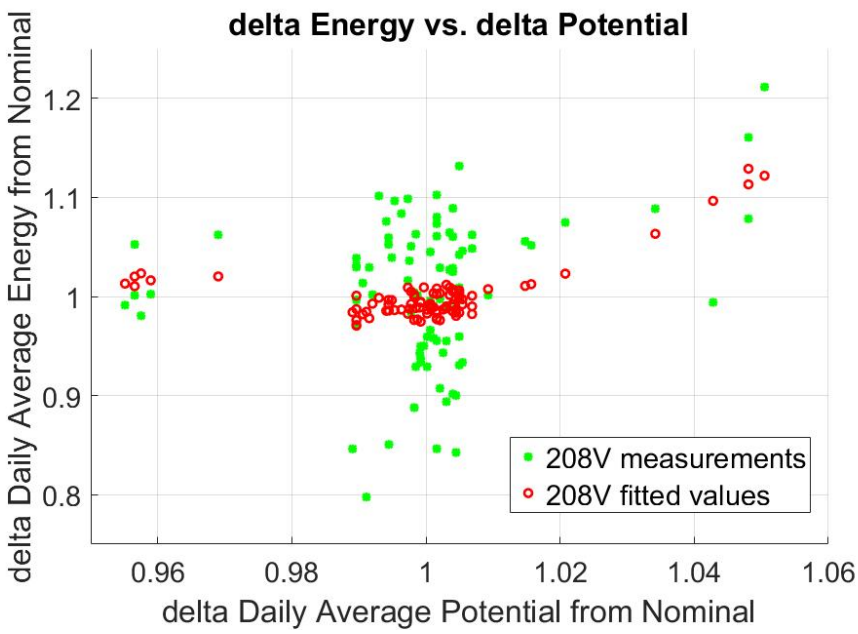


Figure 17 Normalized Voltage vs. Normalized Daily Average Energy in B1588

The previous observations regarding the dependence of the 208V and 480V daily average energy on weather factors were also verified through statistical analysis with R™ software. The daily average temperature and humidity predictors were found to be statistically significant in the 480V daily average energy model but statistically insignificant (low t-value during the t-test for significance) in the 208V daily average energy model. Thus, we reached at the following models for daily average energy in the two circuits:

$$\boldsymbol{E_{208}(KWh) = \alpha_0 + \alpha_1 V_{208} + \alpha_2 V_{208}^2 + error_{208}} \tag{6}$$

$$\boldsymbol{E_{480}(KWh) = \beta_0 + \beta_1 T + \beta_2 H + error_{480}} \tag{7}$$

6.2.5 ENERGY-CVR MODEL PERFORMANCE

The error of fitting the data over the given linear models (6) and (7) is due to special nonlinearities in the data. The MAPE error (Mean Absolute Percentage Error) from in-sample model validation along with the model coefficients are provided in the table below. The CVR factor is also calculated using formula (4). All data was normalized.

Table 5 208V Circuit Model Coefficients and Error Performance for normalized model predictors from Equation (6).

208V Circuit	α_0	α_1	α_2	MAPE
Coefficients	35.74	-70.41	35.66	6.62%
95% Confidence Interval	(10.083, 61.831)	(-122.543, -19.151)	(10.056, 61.724)	

Table 6 208V Model Coefficients Significance based on standardized model predictors

208V Circuit	α_0	α_1	α_2
t-value	0	-2.708	2.745
P-Value (Pr>|t|)	1	0.008	0.007
Standard Error	0.101	4.807	4.807
95% Confidence Interval (2.5%-97.5%)	(-0.20, 0.20)	(-22.57, -3.45)	(3.63, 22.75)

Table 7 480V Circuit Model Coefficients and Error Performance for normalized model predictors from Equation (7).

480V Circuit	β_0	β_1	β_2	MAPE
Coefficients	0.63	0.46	-0.10	6.13%
95% Confidence Interval	(0.485, 0.786)	(0.351, 0.579)	(-0.153, -0.050)	

Table 8 480V Model Coefficients Significance based on standardized model predictors

480V Circuit	β_0	β_1	β_2
t-value	2.33	0.612	-0.295
P-Value (Pr>|t|)	1	$3.03 * 10^{-12}$	0.0001
Standard Error	0.061	0.075	0.075
95% Confidence Interval (2.5%-97.5%)	(-0.12, 0.12)	(0.46, 0.76)	(-0.44, -0.14)

The CVR factor of the 208V circuit is estimated with low confidence due to the large variance of the voltage and voltage squared coefficients. The large variance in the estimation of those coefficients is an outcome of the lack of other predictors that might affect the energy consumption in that circuit other than the voltage reduction/increase. Due to the large variance, it is not possible to provide a confidence interval for the CVR factor of the 208 V circuit. In other words, it is not possible to define with high confidence upper and lower limits of the CVR factor in the 208V circuit.

The model performance over the complete 89 days of measurements is shown below:

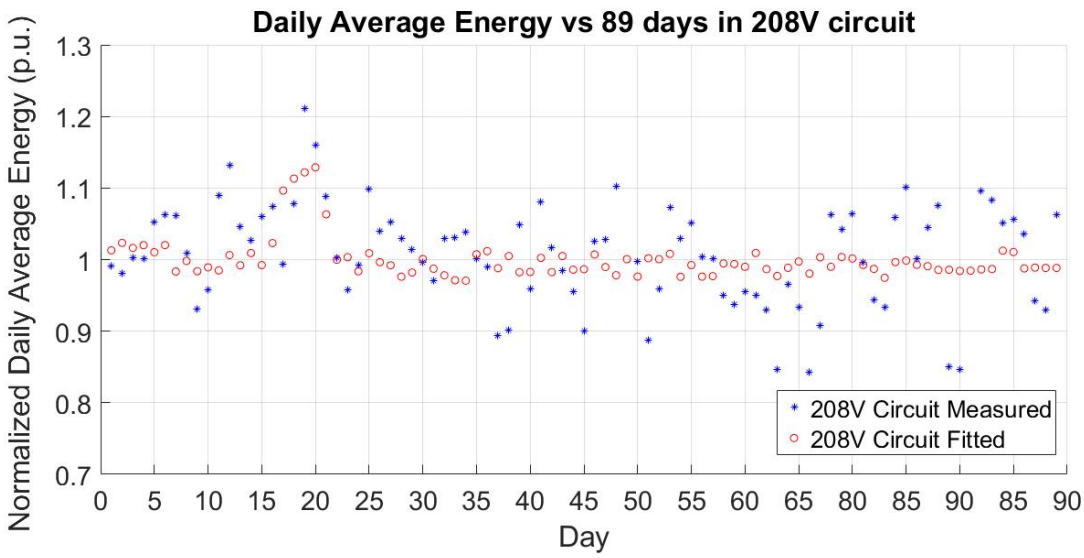


Figure 18 Daily Normalized Average Energy over 89 days in 208V Circuit

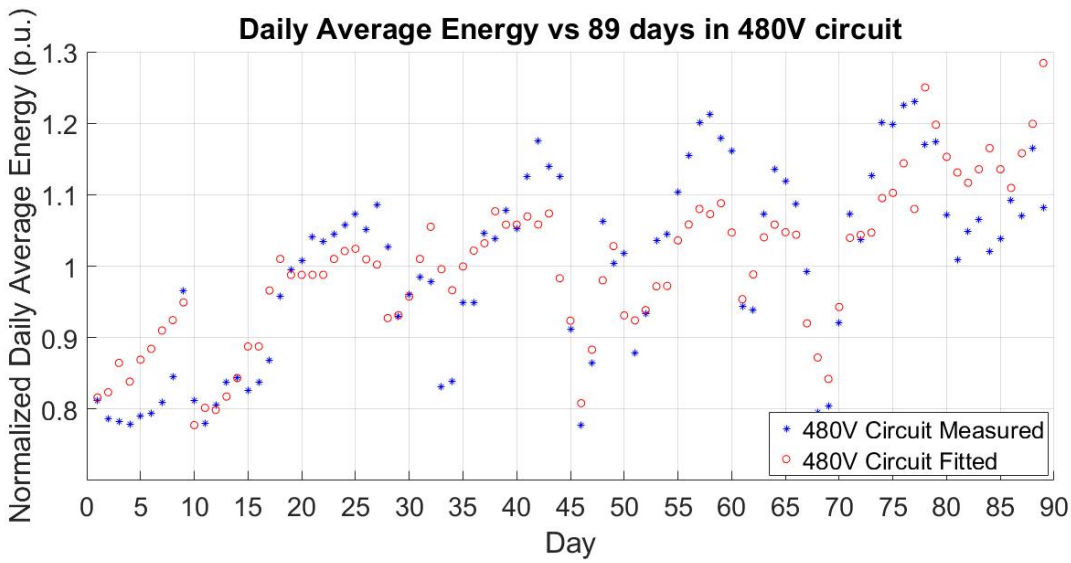


Figure 19 Normalized Daily Average Energy over 89 days in 480V Circuit

6.2.6 RESULTS EXPLANATION

The CVR factor on the 208V circuit was found to be between a constant power and a constant current load behavior. The CVR in circuit 480V is zero because this circuit contains significant closed loop loads which are not affected by the voltage changes. The statistical analysis produced insignificant effect of voltage variation on energy consumption (the voltage and voltage squared coefficients were statistically insignificant and thus excluded from the model resulting in a zero CVR factor according to definition in (4)). In conclusion, the 208V circuit can provide energy savings but the 480V circuit cannot provide a constant rate of savings because of the nature of the motor loads (constant energy consumption regardless the voltage level - knowledge of the operation point can possibly provide power CVR savings for peak load consumption).

Similar results are provided by the Department of Defense of the United Kingdom, which performed a very similar study on CVR for energy savings purposes [21]. Unregulated motors provide potential energy savings if they are operated within a certain region as mentioned in [21] and Figure 4. The experimental results showed a zero CVR in the case of the 408V circuit, which mostly contains regulated motor load and near-constant power lighting technology (see Figure 2). The UK DoD study [21] agrees with the same conclusions and provides a table with the potential savings from different load types which is along with the EPRI study [14] and DoE study [3], the main sources of verification of our results.

Humidity is known to be negatively correlated with temperature (a rule of thumb indicates: "relative humidity doubles with each 20 degree (Fahrenheit) decrease, or halves with each 20 degree increase in temperature" [6]) and this justifies the opposite signs between the daily average temperature and daily average humidity coefficients in model (6). However, humidity is correlated with energy consumption directly through the cooling/heating effect on HVAC (not through Temperature-Energy correlation as analysis showed). A visual representation of the same claim is

[6] http://ocw.usu.edu/Forest_Range_and_Wildlife_Sciences/Wildland_Fire_Management_and_Planning/Unit_4_Temperature-Moisture_Relationship_4.html

given in the figure below.

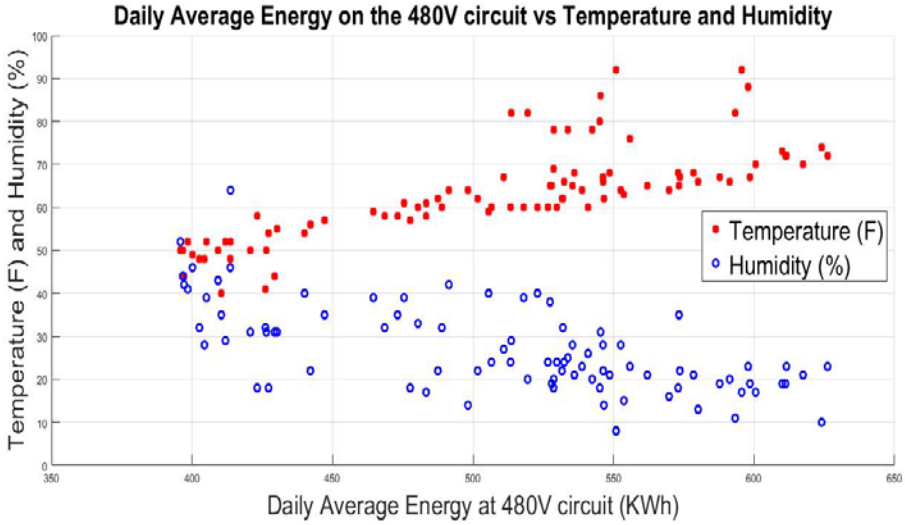


Figure 20: Daily Average Temperature and Humidity vs Daily Average Energy in 480V circuit

6.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The CVR experiment was performed with the assistance of an EVR device connected as shown in the figure below. The device was introduced between the pre-existing Medium Voltage to Low Voltage transformer and the building circuits. The EVR and the taps of the 208V circuit in the building were the two degrees of freedom (points where voltage can be controlled) in this experiment. A picture of the installed EVR equipment is also provided.

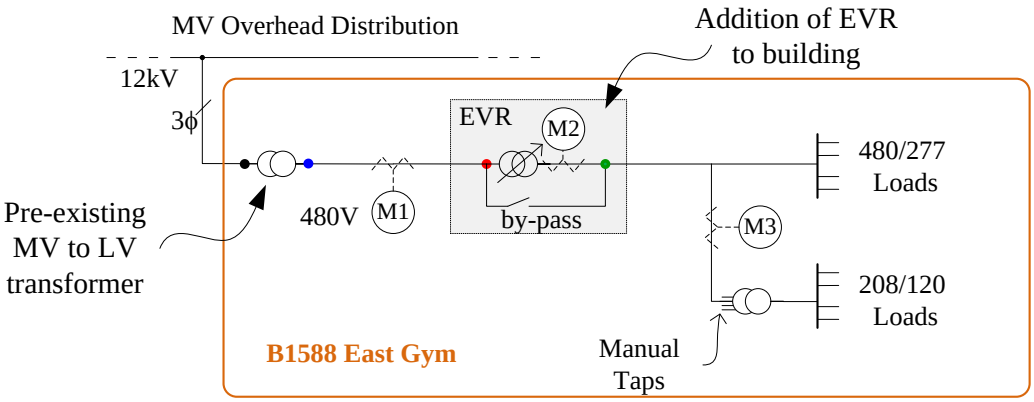


Figure 20 Basic one-line diagram for the layout of the EVR in the building.

Note: to resolve the 480V circuit load separate from the 208V circuit load, data from both Meter #2 and #3 are necessary and the difference was used to calculate the 480V circuit load.

Figure 21 The EVR device installed in the building, and the meter panel display.

Figure 22 Installed Meters and Cellular Router for data retrieval.

6.4 OPERATIONAL TESTING

The EVR settings can be easily set by programming the voltage level on the device. The taps on the 208V circuit transformer require a de-energization of the transformer, changing the tap and then re-energizing the circuit. No other actions were required to perform this experiment.

6.5 SAMPLING PROTOCOL

- *Calibration of equipment*. None was needed. The power quality meters were of sufficient accuracy and came pre-calibrated.
- *Quality assurance sampling*. None was made. The data over the several months were the sampling that fed the analysis.

6.6 SAMPLING RESULTS

The experiments performed are summarized in the table below:

- Several months of data recordings while the EVR output and 208V transformer taps were adjusted to various settings
- Two days of rapid EVR voltage level changes (each 5 minutes).

Table 9 Available Measurements from B1588 after the installation of EVR

Date	Meter # with Measurements Available
1/12/16 - 1/21/16	M3
1/22/16 - 2/2/16	M2, M3
2/3/16	M1, M2, M3
2/6/16 - 2/9/16	M1, M2, M3
2/10/16 - 3/2/16	M2, M3
4/2/16 - 6/22/16	M1, M2, M3
6/22/16	M2, M3

Below an overview of the data collected from the meters is given in several plots:

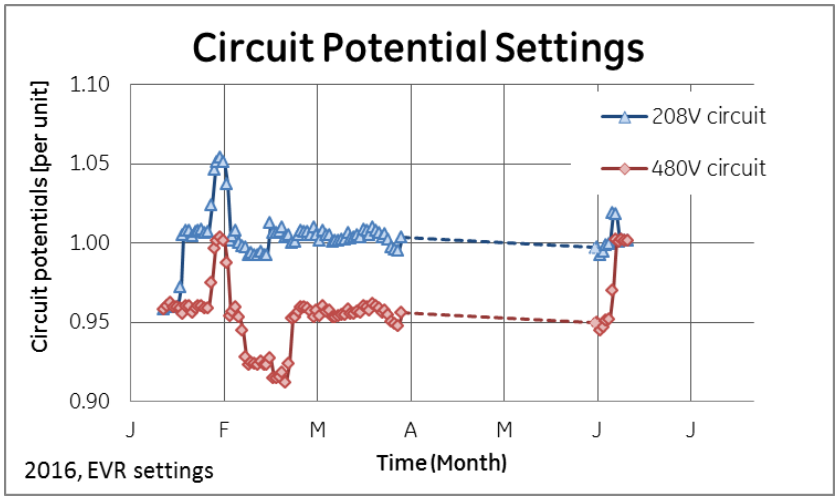


Figure 23 The potentials in both circuits of the building over five months in 2016..

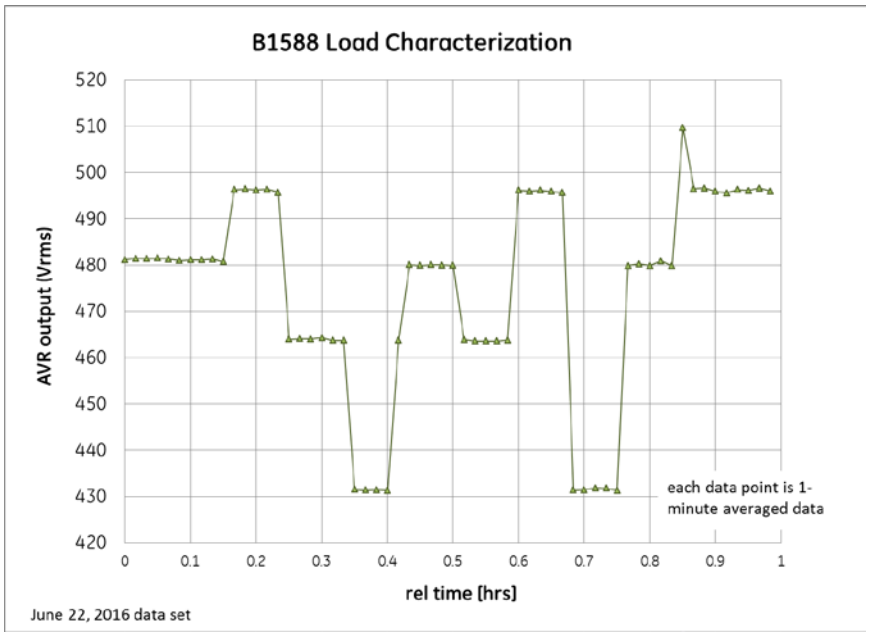


Figure 24 EVR output voltage settings during the Load Characterization Experiments on June 22, 2016.

Weather data used in the analysis was found at the following site location:

https://www.wunderground.com/history/airport/KNXP/2016/5/3/CustomHistory.html?dayend=3&monthend=6&yearend=2016&req_city=&req_state=&req_statename=&reqdb.zip=&reqdb.magic=&reqdb.wmo=&format=6

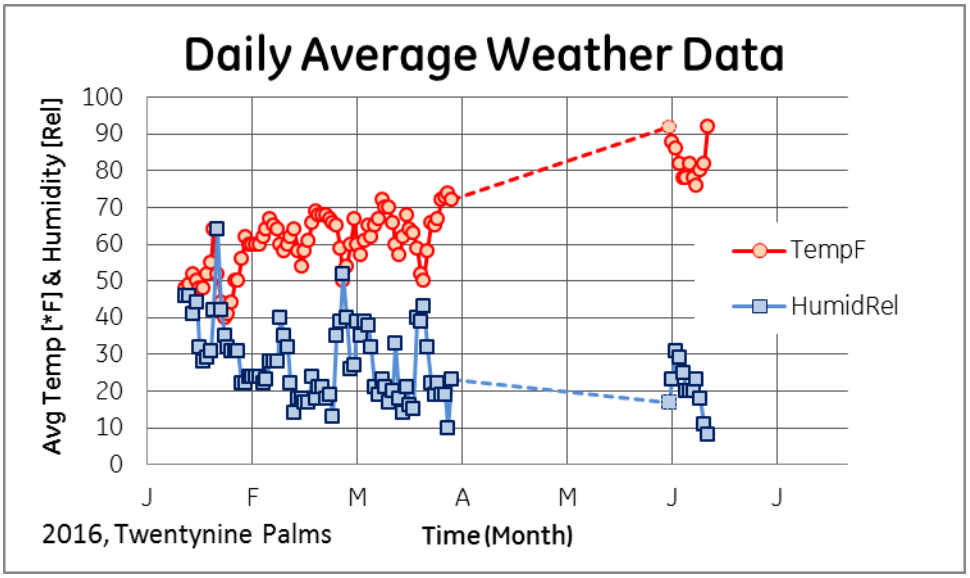


Figure 25 Temperature and Humidity historical data over the five months of 2016 experiments.

7. PERFORMANCE ASSESSMENT

The proposed demonstration will document the energy and peak power reductions of the proposed technology. The demonstration also addresses the question of relative installation costs for a brown field site with typical issues. The combinations of these two give the benefit to cost ratio and a scalability assessment to estimate the total impact to the DoD.

7.1 PEAK POWER REDUCTION

The original hypothesis was that the EVR device will reduce the **peak power** of the building by 4~5%, when the voltage is dropped from 1.0 to 0.95 pu. The collected data from the building load characterization shows that the 208V circuits have a much more resistive characteristic than the 480V circuit, which is nearly constant power. The VSF for B1588 is summarized below in Table 10, and the performance for B1588 is summarized below.

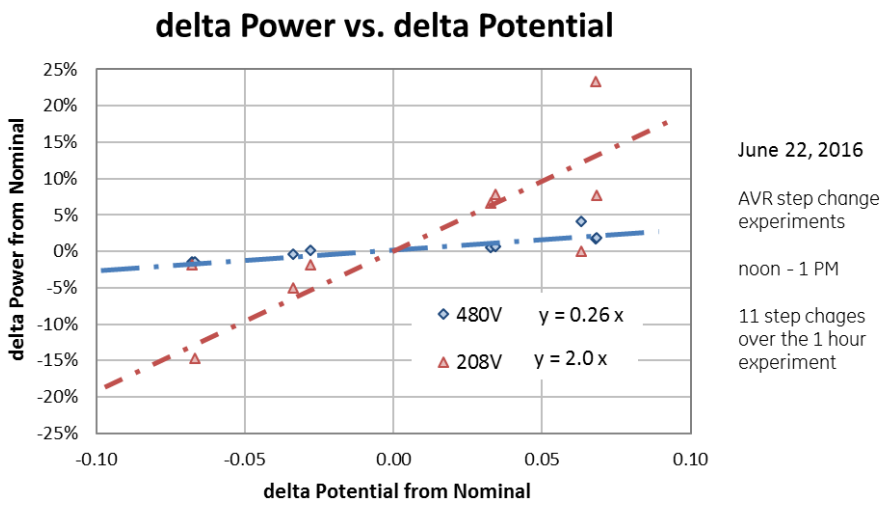


Figure 26 Plot of delta-power vs. delta-potential data points from the load characterization experiment.

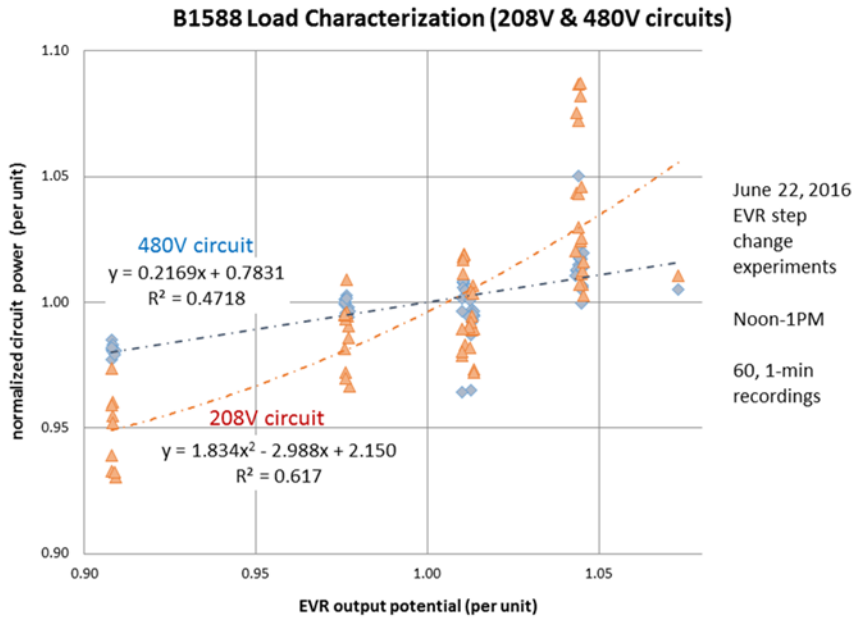


Figure 27 *Plot of all power vs. potential sampled points over the 1-hour load characterization experiment showing a 480V circuit with CVR-power slope of 0.22, and a 208V circuit with a CVR-power slope of 0.7.*

Table 10 *CVR Power factors for B1588 by two estimation methods.*

	dP/dV (11 delta steps) 1-min response	2*Kz + Ki (all 60 recordings) 5-min response	Power Split
208V circuit	2.0	0.7	33%
480V circuit	0.26	0.22	66%
Aggregated	0.83	0.38	100%
Response to -5% voltage	-4.1%	-1.9%	

The VSF results show that for a 5% voltage reduction, the building can achieve a 4-10% peak power reduction on the 208V circuit, and a 1-3.5% peak power reduction on the 480V circuit. The net division of energy consumption for B1588 is approximately 33% on the 208V circuit, and 66% on the 480V circuit, resulting in a total building level peak load reduction of 1.9-5.6%.

This result falls partially in the range of the claim of a 4-5% reduction in peak power from a 5% drop in building voltage level. The findings fall short of the claim as longer response times are considered due to the load in B1588 having more closed loop control which adjusts power consumption based on voltage perturbations.

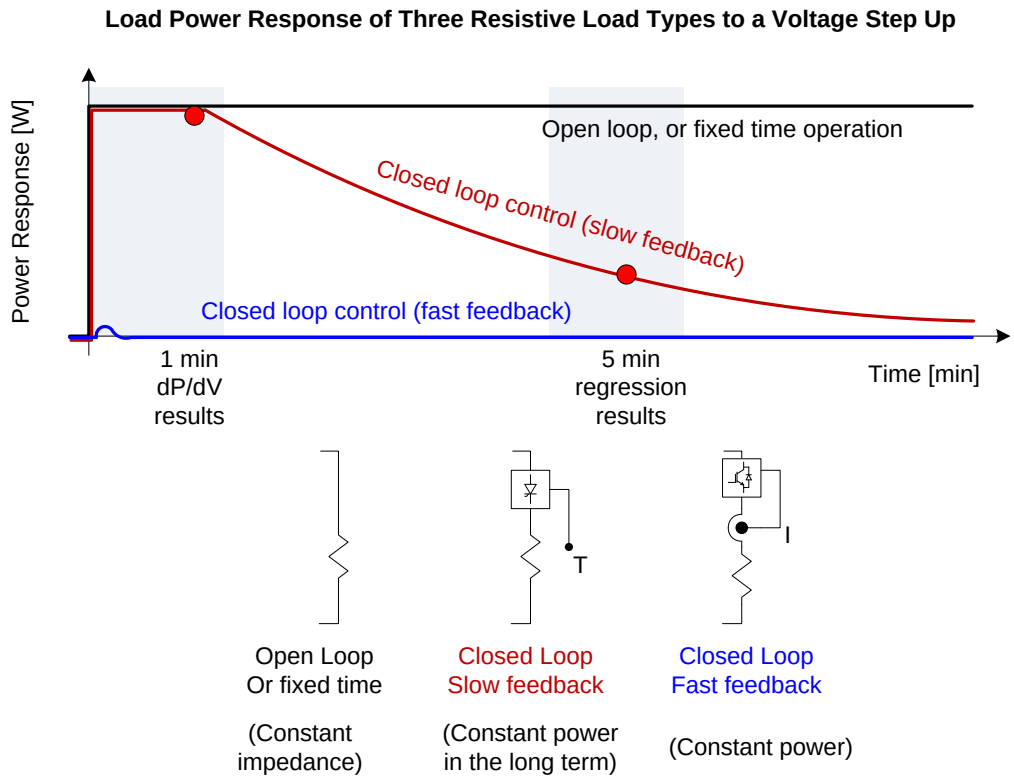


Figure 28 Response of power over time due to a voltage rise applied to three types of resistive loads, showing the probable closed loop response with slow feedback loads within B1588.

7.2 ENERGY CONSUMPTION REDUCTION

The original hypothesis was that the EVR device will reduce the **energy consumption** of the building by 3~4%, when the voltage is dropped from 1.0 to 0.95 pu. The collected data from the building daily energy characterization shows that the 208V circuits has an equal mix of open and closed loop controls, and the 480V circuit is nearly constant energy. The CVR for B1588 is summarized in Table 11 and the performance for B1588 is summarized below.

Table 11 CVR Energy factor for B1588 (from normalized data)

Circuit	CVR Factor	Energy Split
208V	0.91	33%
480V	0	66%
Aggregated	0.3	100%
Response to -5% voltage	-1.5%	

From the CVR factor estimation in the Energy Consumption analysis, it is concluded that a 5%

voltage reduction leads to a 4.55% energy consumption reduction in the 208V circuit. For the 480V circuit the analysis could not reach a high confidence conclusion due to the near zero CVR factor. The net result from an energy split of 33%/66% between 208V and 480V circuits is a total building level energy consumption reduction of 1.5%, which is less than the originally projected outcome due to the load in B1588 being less resistive and more constant power than originally anticipated.

7.3 ENERGY LOSSES DUE TO INEFFICIENCY

EVR inefficiency plays a role in the energy savings calculation. For the day of February 6th, 2016 the total losses on EVR were calculated from the difference between the consumptions of meters 1 and 2. The total energy consumed by losses in the EVR are estimated at 2.1% of the total building energy consumption. The figure below shows the estimated losses in the EVR as a function of total building load.

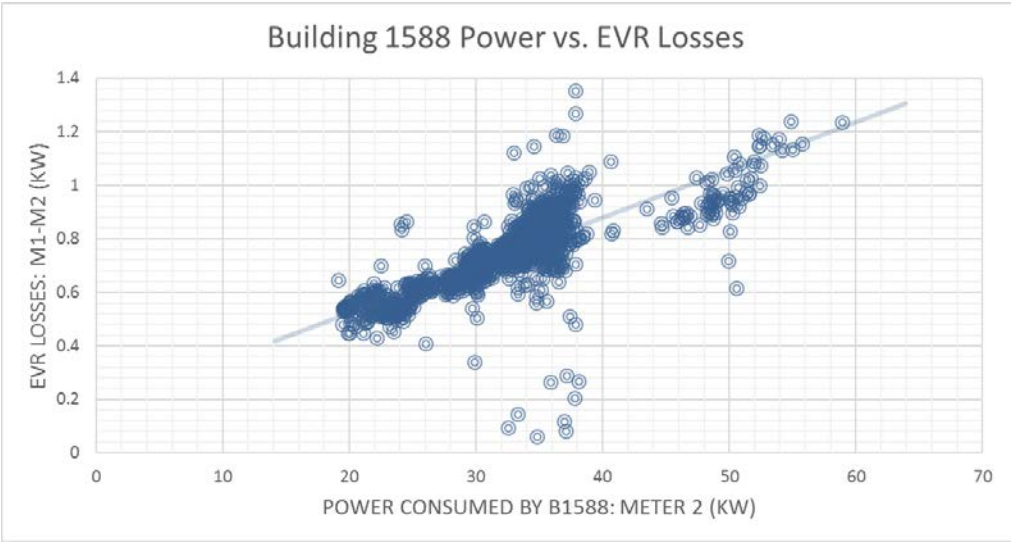


Figure 29 EVR Losses vs. Building 1588 Consumed Power, revealing a 2.1% loss.

This 2.1% loss in the EVR is larger than the estimated 1.5% energy savings achieved by the EVR. The magnitude of the loss could be due to the apparent oversizing of the EVR relative to the building's load (i.e. EVR=150kVA rated, while building load ~ 75kWpeak). But even if the EVR was "right sized" to meet the building's present load demand, the losses would still be on the same order as the observed energy savings and power reductions, thus canceling out any benefit.

Down rating the EVR to a smaller size/rating would improve the magnitude of the losses. Perhaps only applying the EVR to the 208V circuit (which has a meaningful CVR response) and rating the EVR appropriately is one way to help minimize the losses of the unit, and help preserve as much of the benefit as possible.

7.4 QUALITATIVE VOLTAGE IMPROVEMENTS

The original hypothesis was that the EVR would reduce the occurrence of voltage related issues at the building level. No significant building level equipment issues were attributed to voltage sags or events, so no baseline was established against which any improvement could be compared.

Note: Historical voltage droop issues at the base were resolved with the upgrade of the substation equipment feeding the base. The EVR was installed at a later date and did not play any role.

8. COST ASSESSMENT

This section estimates the capital and operational costs of operating the EVR technology at the building level, and assess the financial benefit of operating the EVR technology.

The "current approach" is to operate all transformer equipment at the nominal or "100%" potential taps. The "proposed approach" is split into two methods;

1) use an EVR to reduce the voltage to the building loads in order to achieve CVR,
    a. This method was demonstrated and can be used to dynamically set the voltage at the building level to lowest acceptable level for maximum CVR benefit.
2) manually set the building transformers to a lower tap, where applicable, to induce lower applied voltages, without the use of an EVR.
    a. This method was not demonstrated, but can be used to set the voltage at the building to a reasonably low level based on seasonal or annual estimates of the bases voltage levels, which will return the majority of the CVR benefit.

Site Description:

This cost analysis is being applied to the measured benefits of Building 1588 (East Gym). This industrial building probably does not represent the base as a whole as it is dominated by residential loads.

8.1 COST MODEL

The cost model in Table 12 is for adding a 480V/480V EVR to an existing building, as was done in this ESTCP funded project.

Table 12 Cost model for adding an EVR to a brownfield site.

Cost Element	Data Tracked	Estimated Cost
CapEx	Quotes for hardware	150 – 200 [$/kVA]
Installation	Professional installation	3,000 [$/install]
Consumables	operation over 6 months.	none expected
OpEx	cost of electricity to cover losses and inefficiency	700 [$/kVA/year] (2% of full rating as loss)
Lifetime	projected based on similar equipment	15 ~20 years
Misc	training or other costs	none

The main cost driver for the EVR is the special wound LV-to-LV transformer (or autotransformer) on which the unit is based. Two lower cost options to the baseline case are:

- Combined MV to LV transformer with multiple taps and EVR functionality
- An EVR "kit" to add to an existing building transformer with taps available.

These alternate cost models represent a potential low cost way to integrate the building level voltage control technology with reduced losses.

8.2 COST ANALYSIS AND COMPARISON

8.2.1 COST ASSESSMENT

The Cost Assessment for the EVR technology was based on a simple return-on-investment model, and was compared with a secondary method to achieve similar performance with lower investments.

Two configurations were used in this analysis, the first one which could dynamically adjust voltage to a pre-defined setting which gives maximum benefit, and a second method that was much lower cost but would not achieve as high a benefit.

Note: the below tables do not consider other EVR implementation strategies where only the 208V circuit has an EVR applied. (as was introduced in Section 7.3).

Table 13 Two configuration options for achieving voltage adjustment.

	Manually set taps	EVR dynamically set taps
MV to 480V	MV to 480V isolation transformer (pre-existing)	
480V adjustment	Manual selection of taps on MV transformer for reduced voltages	Separate 480V to 480V transformer with multiple output taps & EVR equipment
480 to 208V	480V to 208V isolation transformer with high side taps (pre-existing)	
208V adjustment	Manually selected taps on “high side” of transformer for reduced voltages	Manually selected taps on high side of transformer

Table 14 Two configuration options with equipment and labor cost estimates.

	Manually set taps	EVR dynamically set taps
MV to 480V	Pre-existing, no new costs (0 $/kVA)	
480V adjustment	No equipment costs, $600 Labor (de-energize & set taps)	150 $/kVA + $3k labor
480 to 208V	Pre-existing, no new costs (0 $/kVA)	
208V adjustment	No equipment costs, $600 Labor (de-energize & set taps)	EVR lowers voltage for both circuits

8.2.2 BENEFIT ASSESSMENT

The benefit of applying lower voltages to building used the below assumptions.

List of assumptions:

Price of electrical energy:	$0.07/kWh	flat rate for energy at the base
Price of peak power:	$15/MW	peak power charge per 28 day billing period
Building average power	50 kW	
Building peak power	75 kW	
CVR energy savings:	-1.5%	energy savings (without EVR losses)
CVR peak power reductions:	-1.9%	peak power reductions from 5% voltage drop
EVR energy/power losses:	1.5%	(thus nullifying any energy or power savings benefit)

Table 15 Simple Cost and Benefit assessment for two voltage setting strategies applied to a building with 75kW peak power consumption.

	Manually set taps	EVR dynamically set taps
Initial Costs (Equipment + Labor)	$600	$14,250
Recurring costs (over the 20 year life)	None	none
Energy Savings	-1.2% (80% of observed)	0% (EVR losses erode benefit)
Peak Power Reduction	-1.5% (80% of observed)	0% (EVR losses erode benefit)
Energy bill savings	$222 / year	$0 / year
Demand Charge reductions	$368 / year	$ 0 / year

Table 15 Simple Cost and Benefit assessment for two voltage setting strategies applied to a building with 75kW peak power consumption. Table 15 shows that the EVR has no measurable benefit in the example building. This is due to the EVR having a separate transformer inside with multiple taps. Rather a simpler method of manually adjusting the taps of the pre-existing transformers were 80% of the claimed performance benefit can be had at near zero cost.

9. IMPLEMENTATION ISSUES

Below is a summary of implementation issues.

Lesson Learned:

- Internal to building electrical equipment rooms are not often well suited or able to house an EVR unit, due space constraints and wire routing issues.
- Outside sites have more space, but require outdoor rated equipment (NEMA outdoor rated..) and more maintenance due to dirt and debris issues.
- Manual tap changes by electricians requires the equipment to be de-energized.
- De-Energized Tap Changers (DETC) or "dial tap" changers on a pad mount and clam-shell residential transformers is an easy way to turn down voltages. These devices are normally always set to the "100%" or "nominal" position.

Potential Regulations:

- No significant regulations are predicted that affect the application of voltage regulating devices.
- New Smart Inverter requirements may help support voltage regulation strategies, but it is unclear whether these devices will encompass voltage reduction strategies.

Decision Making Factors:

- A decision to reduce a building's voltage level should be based upon knowledge of the loads within that building. Even then, a decision to opt for voltage reduction for energy or peak power reduction needs to be compared with other efforts to modernize the loads and apply alternative control strategies (closed loop controls).
- Distributed solar power has an impact on local voltage profiles. An EVR can help mitigate voltage swings and their impact on sensitive equipment. But the application of an EVR must be weighed against modernizing the equipment which is sensitive to voltage perturbations.

Procurement Issues:

- No significant procurement issues. EVR technology is generally available and often applied to US Embassies in developing nations where poor voltage quality is an issue.

10. RESULTS & DISCUSSION

Two key results of this study and demonstration are:

- Adding a separate building level EVR with integral multi-tap transformer does not have any benefit with respect to CVR methods. Instead, many pre-existing transformers have DETC's that can be manually adjusted to achieve some level of benefit for very low cost.
- Feeder voltage control and profile shaping is difficult, and requires coordination between the feeder head load tap changer and any downstream devices.

Additional results and discussion are given below.

10.1 CVR ASSESSMENT EFFORTS

It is difficult to measure the benefit of CVR methods. Months of building data was recorded and statistical analysis were applied to determine the approximate CVR factors for both 480 and 208V circuits. No simple way exists today to assess the CVR factors for a base or a building.

10.2 TRENDS IN ELECTRICAL LOADS

The characteristics of electrical loads are changing which erode peak power reductions and energy consumption reductions from CVR methods. More specifically the trends impacting either peak power and/or energy reductions are:

- Lighting has moved from incandescent (resistive) to florescent and now LED, which have a constant power characteristics that does not respond to voltage reductions.
- Building mechanical infrastructure supporting air handling and environmental controls are moving from line fed motors operating continuously to electronically modulated pumps regulated by closed loop controls. This migrates these loads towards constant power and constant energy.
- Laundry drying loads are migrating away from electric-constant run time units, to temperature or dryness controls which result in constant energy (CVRenergy=0).
- More motor loads are being fed by power converters rather than simple line fed electric machines, which results in more constant power loads (CVRpower =0)
- More processes are applying closed loop controls, rather than simple timer modes, which moves these loads to constant energy (CVRenergy=0),

10.3 DISTRIBUTION LEVEL VOLTAGE CONTROL & TRENDS

More distributed generation such as Solar Power, will result in elevated voltage profiles on feeders, which originally only featured voltage droop. But the impact may be negligible as loads become less sensitive to voltage.

10.4 PRACTICAL STEPS FOR REDUCING ENERGY CONSUMPTION

Building Mechanical and Electric Equipment audits will quickly reveal where there are loads which are wasteful and in need of update or repair. These audits can be a precursor to applying

any CVR methodologies and may give insights into more cost effective solutions to energy consumption and peak power reductions.

Setting manual transformer taps to lower settings is a reasonable strategy for heavily resistive loads or buildings to reduce peak power demands.

10.5 AUDIT OF TWENTYNINE PALMS BUILDING LOADS

An appendix is added which audited the MCAGCC at Twentynine Palms.

A survey of the load types, and an assessment of the base's transformer types is given.

11. REFERENCES

1. EW 201147 Fact Sheet from the ESTCP website: https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Microgrids-and-Storage/EW-201147

2. Conservation Voltage Reduction, Phillip Anderson, Idaho Power, 2013 https://www.idahopower.com/pdfs/AboutUs/PlanningForFuture/irp/2013/DecMtgMaterials/ConservatioVoltageReduction.pdf

3. PNNL 19596, July 2010 http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19596.pdf

4. R. Comfort , A. Mansoor and A. Sundaram "Power quality impact of distributed generation: effect on steady state voltage regulation", PQA 2001 North America Conf., 2001 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.202.5283&rep=rep1&type=pdf

5. Capacitor Application Issues, Eaton Corporation, Thomas Bloomberg, Daniel Carnovale, whitepaper on www.eaton.com

6. EPRI, 2011, Volt/Var Control and Optimization Concepts and Issues. [Online]. Available: http://cialab.ee.washington.edu/nwess/2012/talks/uluski.pdf

7. Evaluation of Conservation Voltage Reduction (CVR) on a National Level, US. Department of Energy, July 2010, Report.

8. Kirshner D., "Implementation of Conservation Voltage Reduction at Commonwealth Edison", *IEEE Transactions on Power Systems*, vol. 5, pp. 1178-1182, 1990.

9. Begovic M., Novosel D., Milosevic B. and Kostic M.,: Impact of Distribution Efficiency on Generation and Voltage Stability, presented in *Proc. 33rd Annual Hawaii Int. Conf. System Sciences, 2000*, 2000, p.*7* pp.

10. Wang Z., and Wang J. "Review on Implementation and Assessment of Conservation Voltage Reduction", *IEEE Transactions on Power Systems*, vol. *29*, no. *3*, pp. *1306-1315*, May 2014.

11. ANSI, "ANSI Standard C84.1-1995 Electric Power Systems and Equipment Voltage Ratings (60 Hz)," 1995.

12. Kennedy B. and Fletcher R., "Conservation Voltage Reduction (CVR) at Snohomish County PUD", *IEEE Transactions on Power Systems*, vol. *6*, pp. *986-998*, 1991.

13. Scalley B. L. and Kasten D. G., "The Effectws of Distribution Voltage Reduction on Power and Energy Consumption", *IEEE Transactions on Power Systems*, vol. E2-4, No. 3, pp. 210-216, 1981.

14. EPRI, 2001, PQ Commentary. [Online]. Available: http://www.smartgridnews.com/artman/uploads/1/sgnr_2007_1208.pdf

15. Chen M., Shoults R. and Fitzer J., "Effects of Reduced Voltage on the Operation and Efficiency of Electric Loads", in *EPRI, Arlington: University of Texas, EL-2036 Volumes,* 1981, vol. 1, p. 1419-1.

16. Wilson T., 2003, AdaptiVolt Based CVR in Industrial Applications Technical Synopsis. [Online]. Available: http://utilidata.com/as-sets/docs/white_papers/UtiliData_Technical_Synopsis_Industry_.pdf

17. Schneider J. F., Tuffiner F. and Singh R., 2010, Evaluation of Conservation Voltage Reduction (CVR) on a National Level. [Online]. Available: http://www.pnl.gov/main/publications/external/tech-nical_reports/PNNL-19596.pdf

18. Wilson T. L., "Measurement and Verification of Distribution Voltage Optimization Results", in *Proc. 2010 IEEE Power and Energy Society General Meeting*, 2010, pp. 1-9.

19. RTF NWCouncil, 2011, Standard Protocol #1 for Automated CVR. [Online]. Available: http://rtf.nwcouncil.org/subcommittees/cvr/

20. RTF NWCouncil, 2012, CVR Standard M&V Protocol #1. [Online]. Available: http://rtf.nwcouncil.org/subcommittees/cvr/

21. Justifying and Delivering Voltage Optimization on the Mod Estate, UK Department of Defense Estate Management, January 2010. Practitioner Guide.

12. APPENDICES

12.1 SCHEMATICS

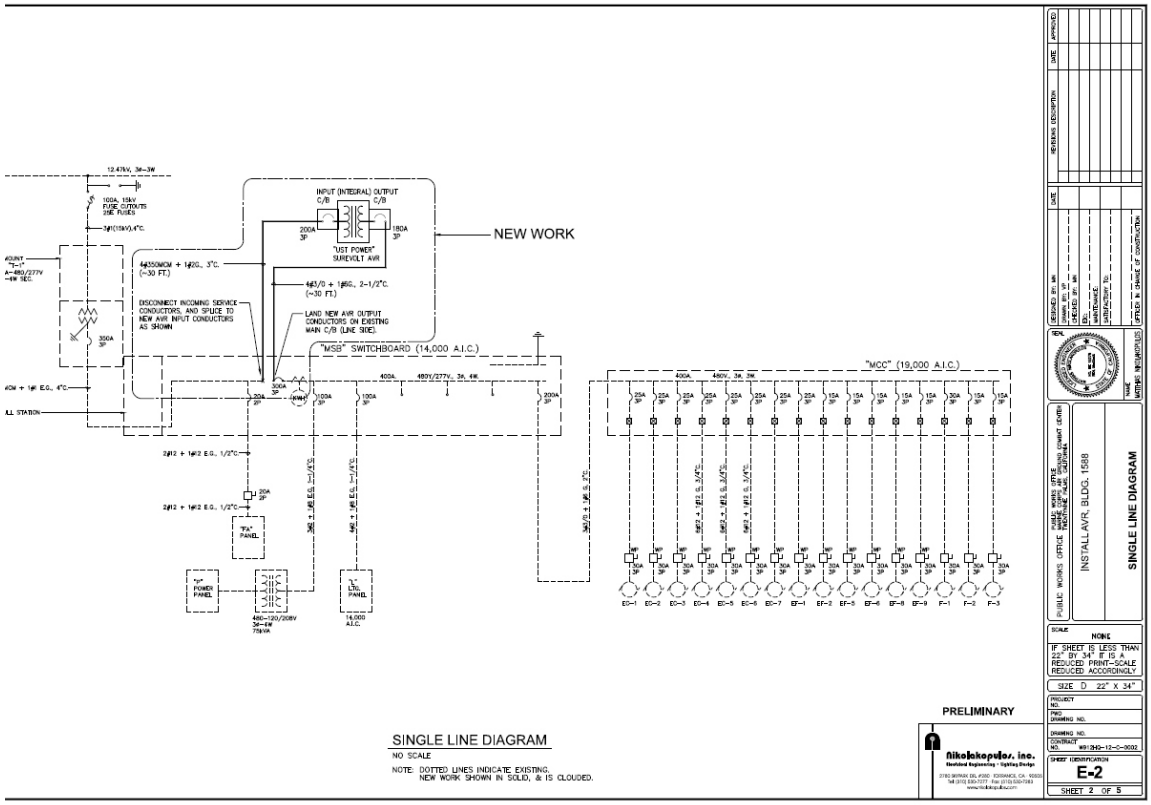


Figure 30 Example one-line diagram detail for the inclusion of the EVR at B1588?

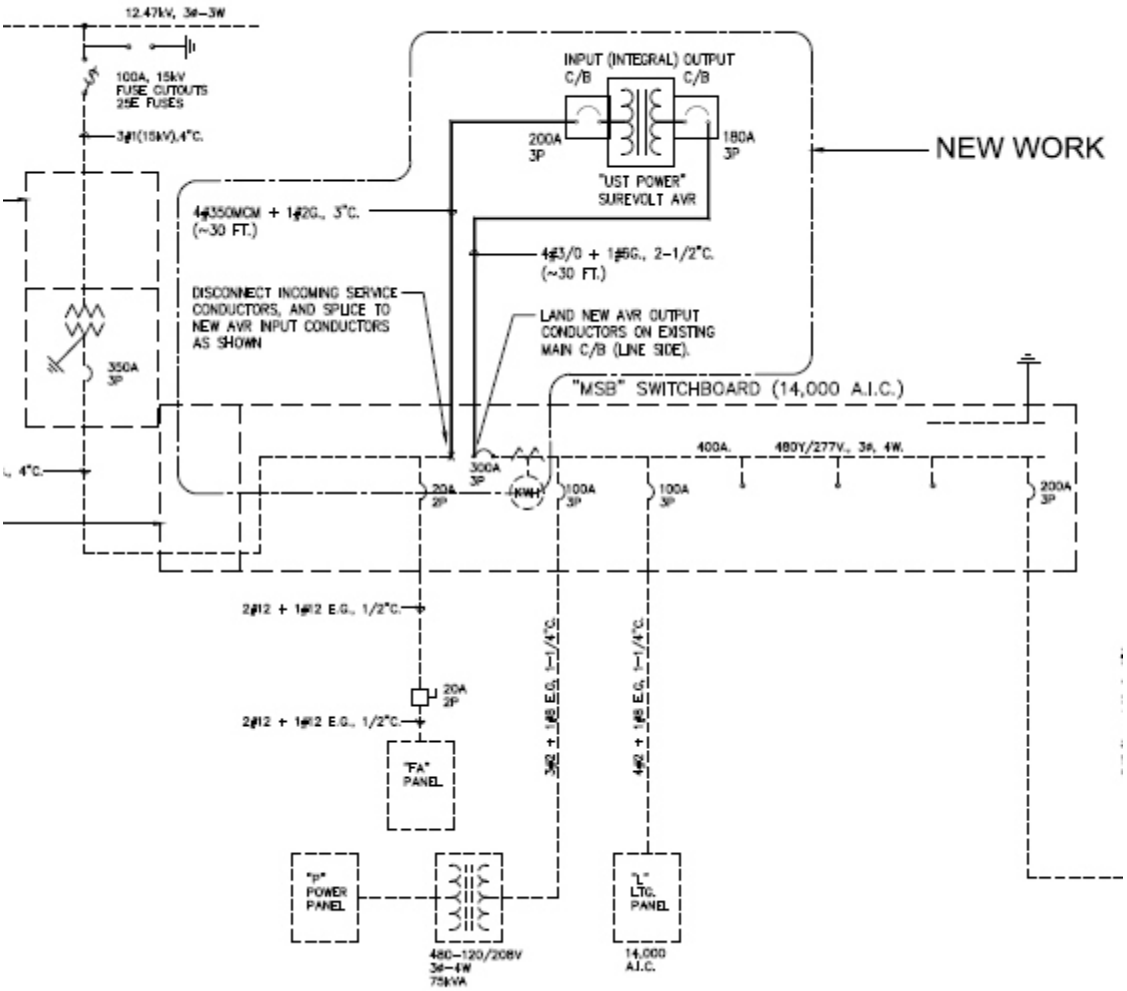


Figure 30 Details of EVR installation in B1588.

12.2 DATA RECODRING METER DEVICES

Data measurements were implemented via utility-grade electric power meters. These are common in the industry.

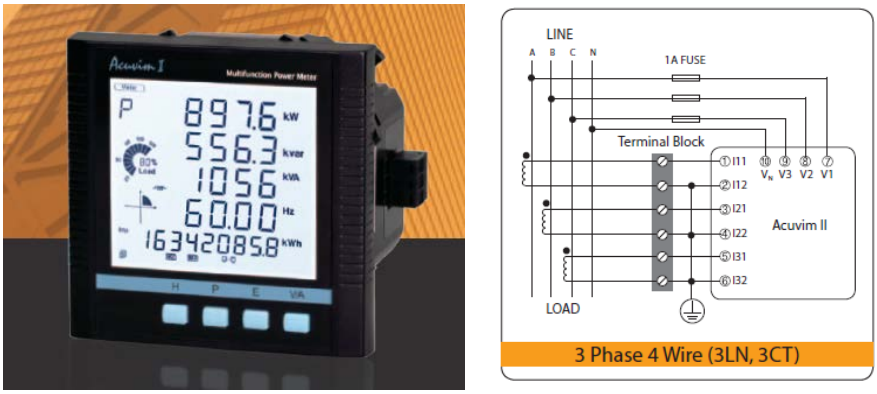


Figure 31 Typical electric power quality meter for measuring 3-phase circuits.

12.3 B1588 VOLTAGE QUALITY

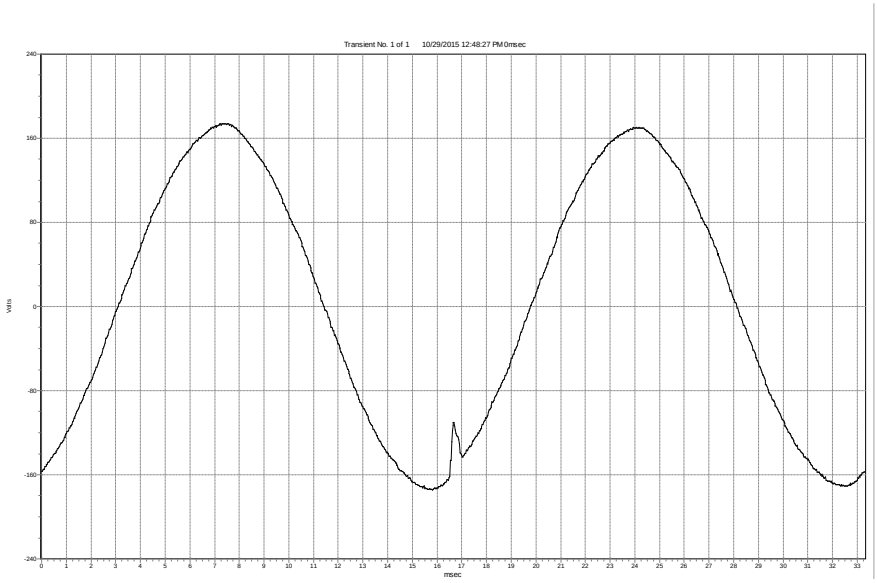


Figure 32 Example voltage quality event recorded at a convenience outlet inside B1588 showing only a minor notch from a switched load.

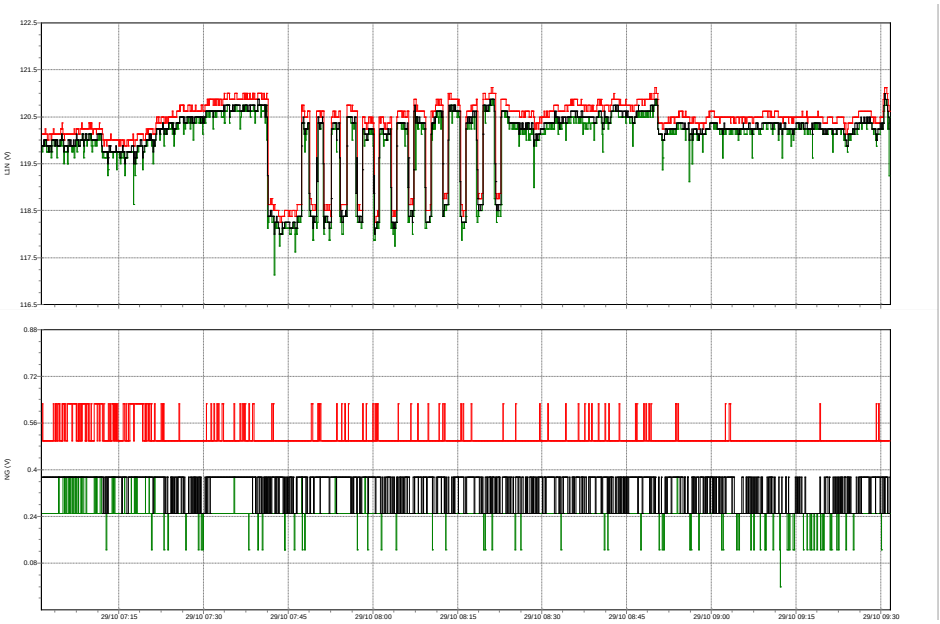


Figure 33 Typical 3-phase line-neutral potentials, and neutral to ground, at output of 208V transformer over the course of several hours, showing +/- 1% variation probably due to droops from building loads (e.g. a resistive dryer load, or air handler).

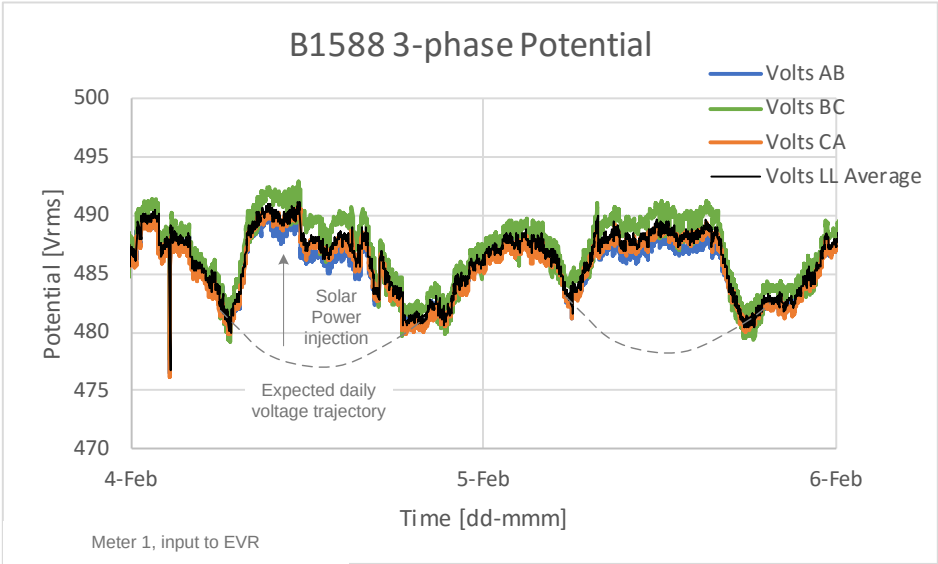


Figure 34 *Typical potential for B1588 at meter 1 over two days, showing +/- 1.5% variation and an average input of 1.01 per unit (485Vrms) and a probable effects from solar power injection into the feeder during the middle of day.*

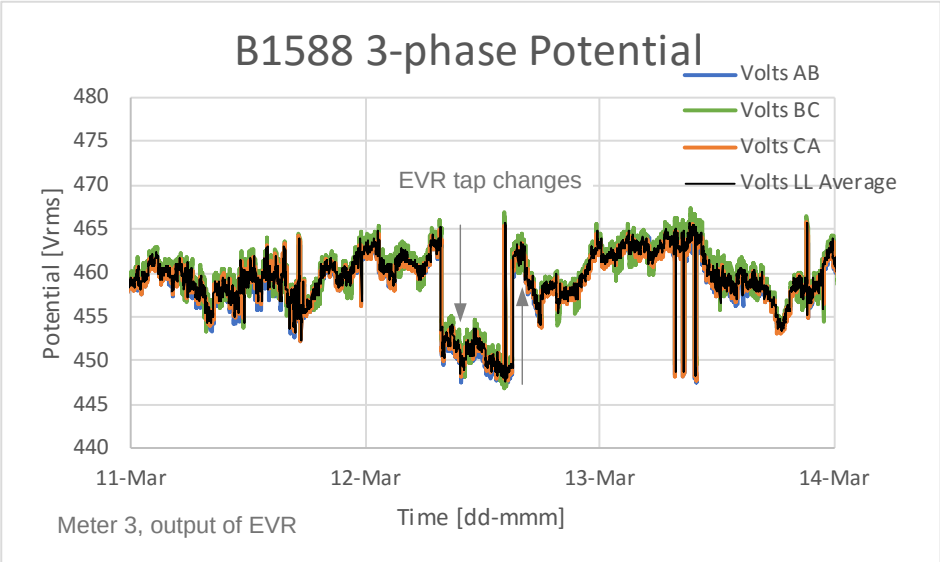


Figure 35 *Measured potentials for B1588 at meter 3 (EVR output) over several days showing +/- 1.5% variation and an average of 0.95 per unit (456Vrms) and effects from the EVR tap changing several times over three days.*

12.4 ENERGY MODEL RESIDUAL ANALYSIS

In this section, the details of the statistical analysis are displayed for completeness.

Table 16 Residuals at 208V Circuit

Residuals 208V	Min	1Q	Median	3Q	Max
	-5.094	-0.487	0.2	0.618	1.426

Table 17 Residuals at 480V Circuit

Residuals 480V	Min	1Q	Median	3Q	Max
	-1.546	-0.402	-0.028	0.490	1.145

Table 18 Error Performance at 208V Circuit

208 V Model	
Residual Standard Error	0.9546
Multiple R Squared	0.1094
Adjusted R Squared	0.08866
F Statistic	5.28
P Value	0.00687
Degrees of Freedom	86

Table 19 Error Performance at 480V Circuit

480 V Model	
Residual Standard Error	0.5809
Multiple R Squared	0.6702
Adjusted R Squared	0.6625
F Statistic	87.37
P Value	< 2.2e-16
Degrees of Freedom	86

The following plots verify the performance of the linear models used to fit the daily average energy consumption in the two circuits. The residuals vs. fitted values plots show an almost constant

relationship which means that the variance of the residuals is small related to the fitted values in both circuits. The QQ plots show a straight line of about 45 degrees, which is an indication of good normalization of the predictors in the models. More specifically, standardizations were applied so that the data follow a standard distribution of mean zero and sigma 1 before fitting. The previous observations increase the validity of a linear regression model according to the assumptions of linear regression theory.

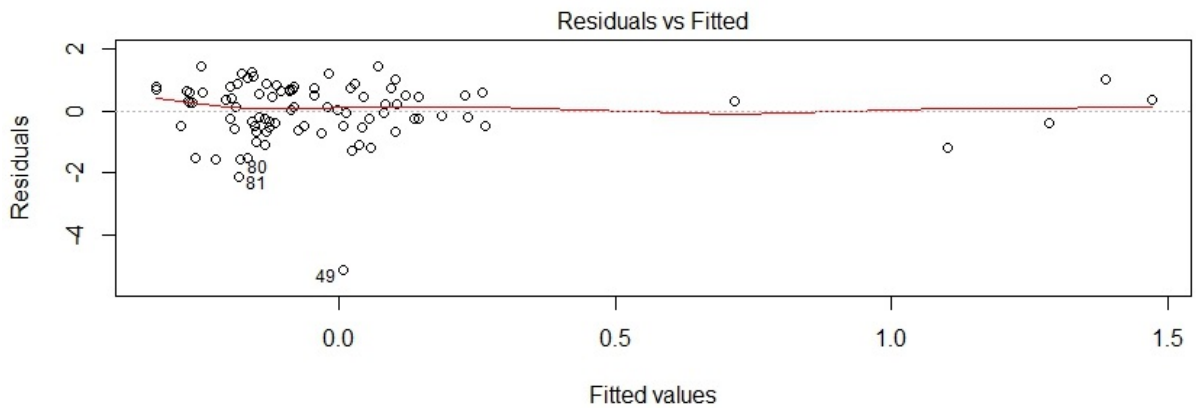


Figure 36 Fitted Values vs. 208V Model Residuals

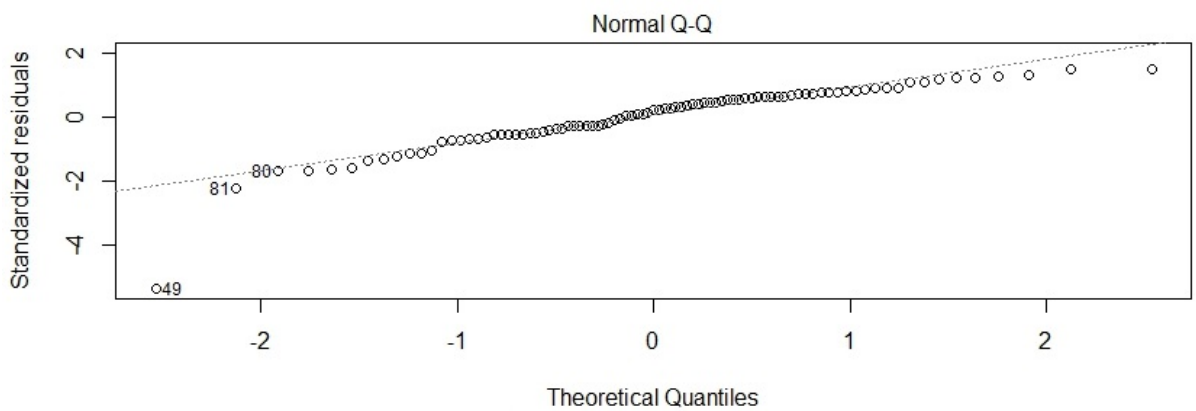


Figure 37 Theoretical Standardized Residuals vs. 208V Model Standardized Residuals

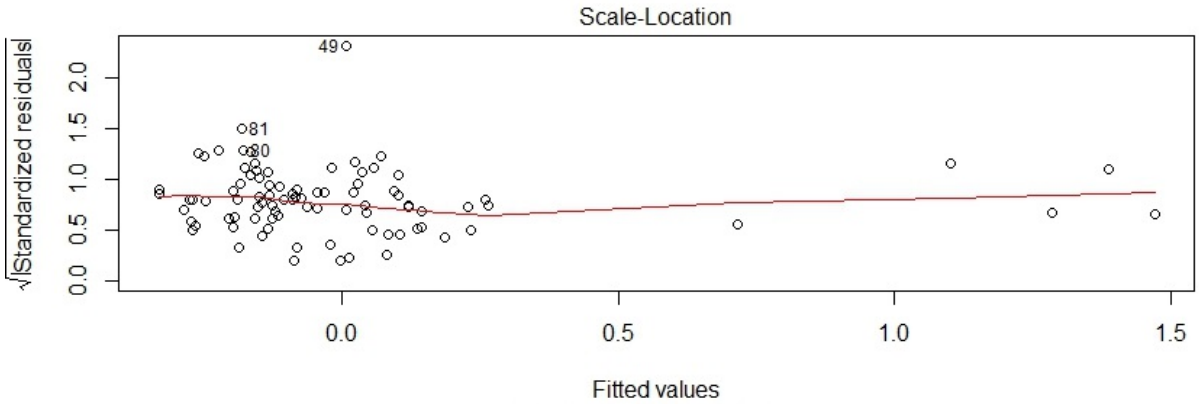


Figure 38 Fitted Values vs. 208V Model Standardized Residuals Square Root

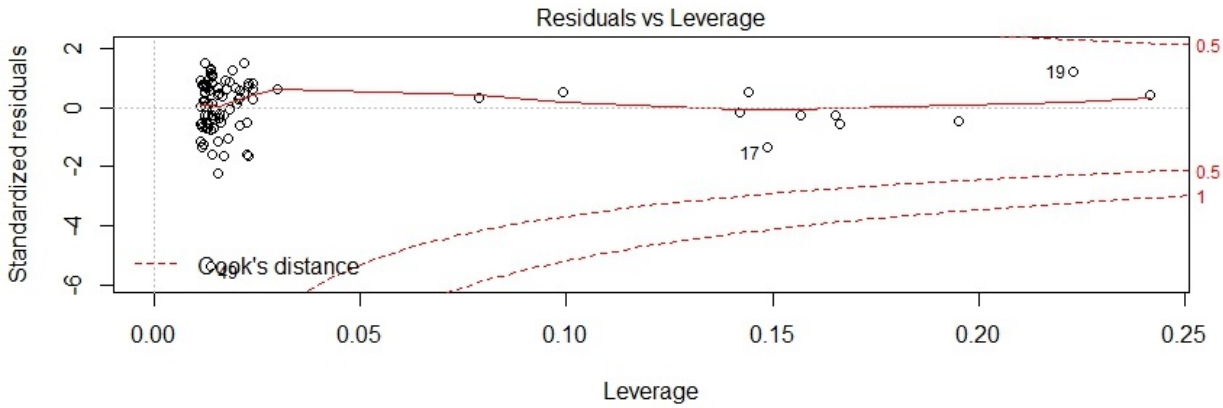


Figure 39 Leverage vs. 208V Model Standardized Residuals

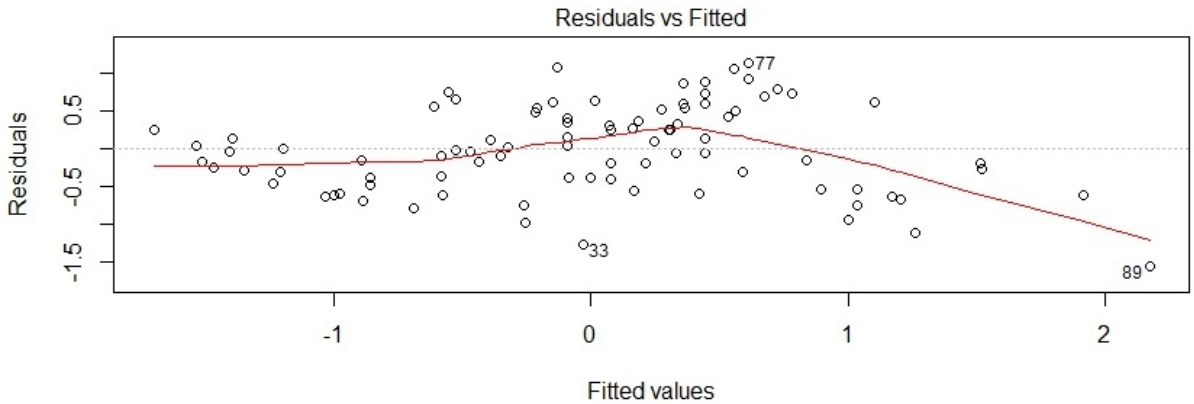


Figure 40 Fitted Values vs. 480V Model Residuals

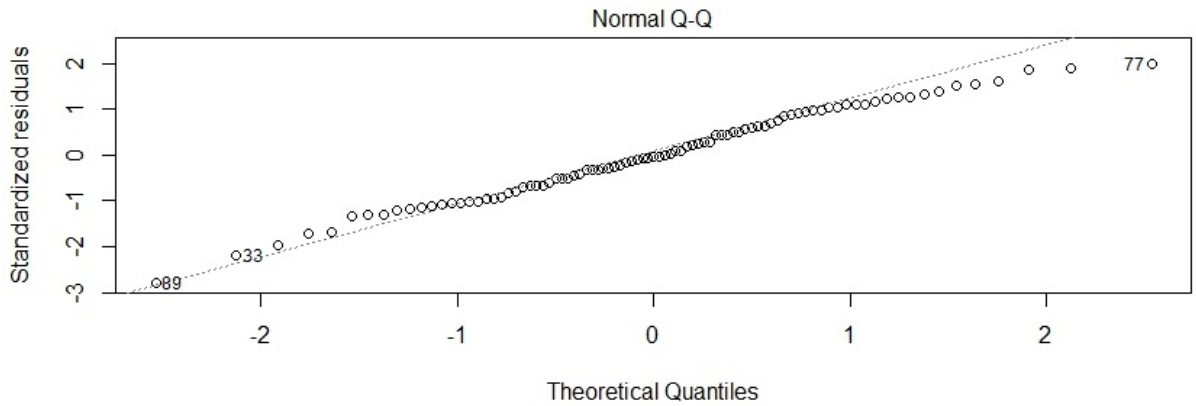


Figure 41 Theoretical Standardized Residuals vs. 480V Model Standardized Residuals

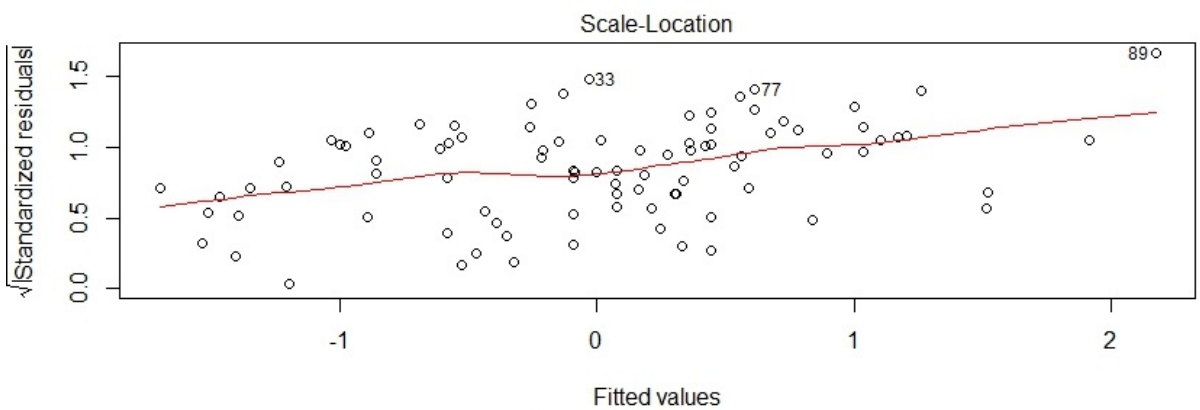


Figure 42 Fitted Values vs. 480V Model Standardized Residuals Square Root

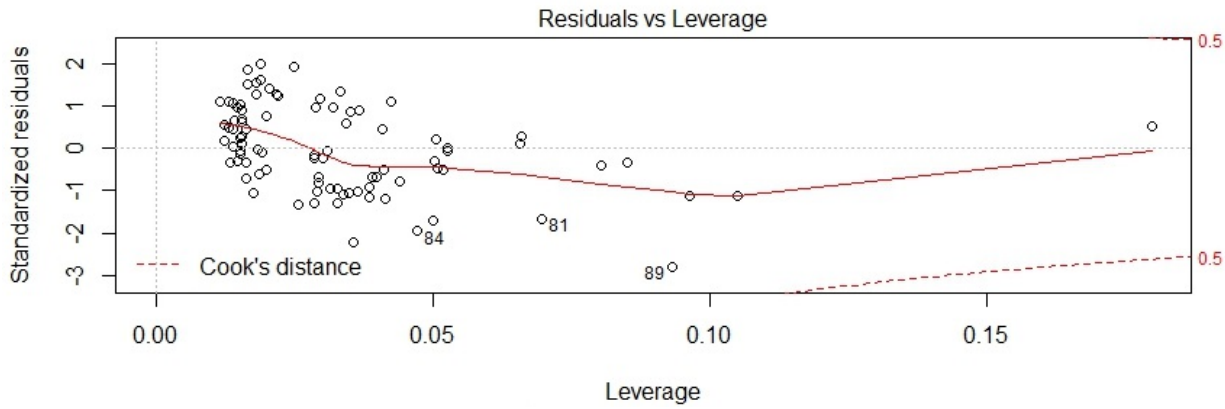


Figure 43 Leverage vs. 480V Model Standardized Residuals

11.4 ENERGY MODEL PREDICTOR ANALYSIS: BOX PLOTS

The following boxplots provide a better overview of the date related to daily average energy consumption in both 208V and 480V circuits. We observe that the 208V energy consumption is more affected from the human occupancy than the 480V. This is derived from the fact that the days of the week or the month of the year shows a human pattern consumption other than weather conditions correlation. On the other hand, the 480 V circuit shows a trend in the month of the year boxplot which is highly correlated with temperature. No pattern or information could be extracted from the day of the month boxplot because none of the loads is directly correlated with the day of the month. Human occupancy shows a trend with the day of the week and special events (i.e. more soldiers were introduced to this base after April, holiday etc) and weather conditions show a trend with the month of the year other than the day of the week or the day of the month. It is possible that the 208V circuit can increase its model error performance if the day of the week was introduced in the model.

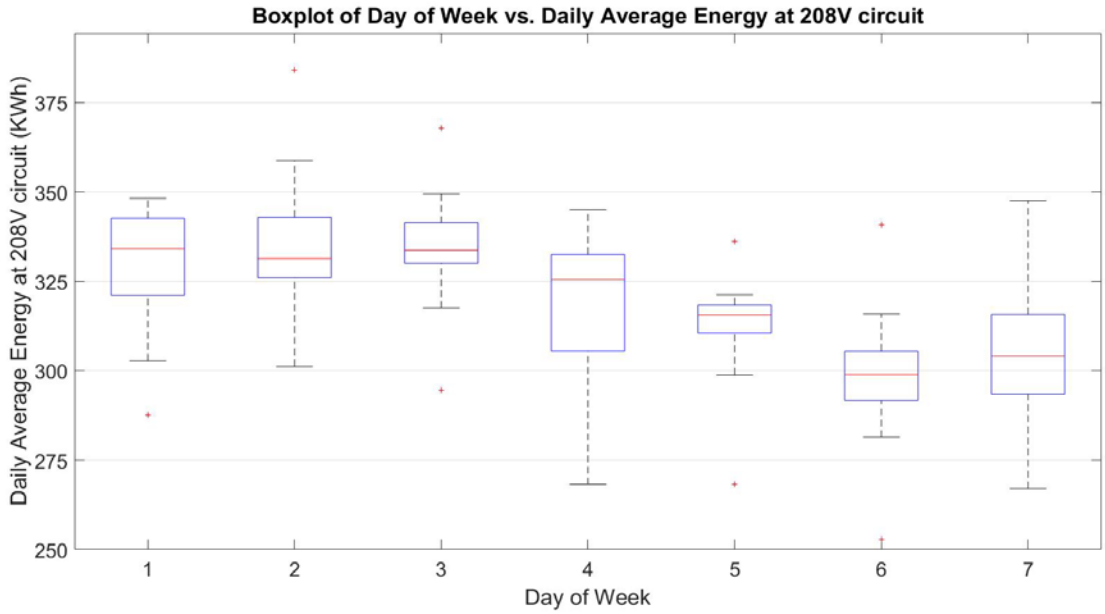


Figure 44 Day of Week vs. Daily Average Energy at 208V Circuit

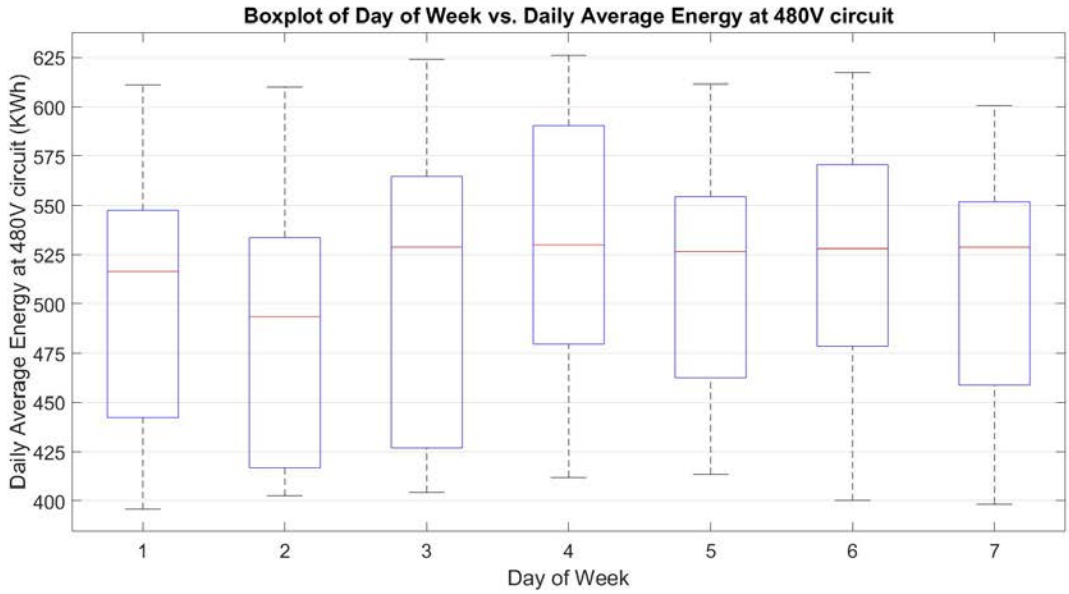


Figure 45 Day of Week vs. Daily Average Energy at 480V Circuit

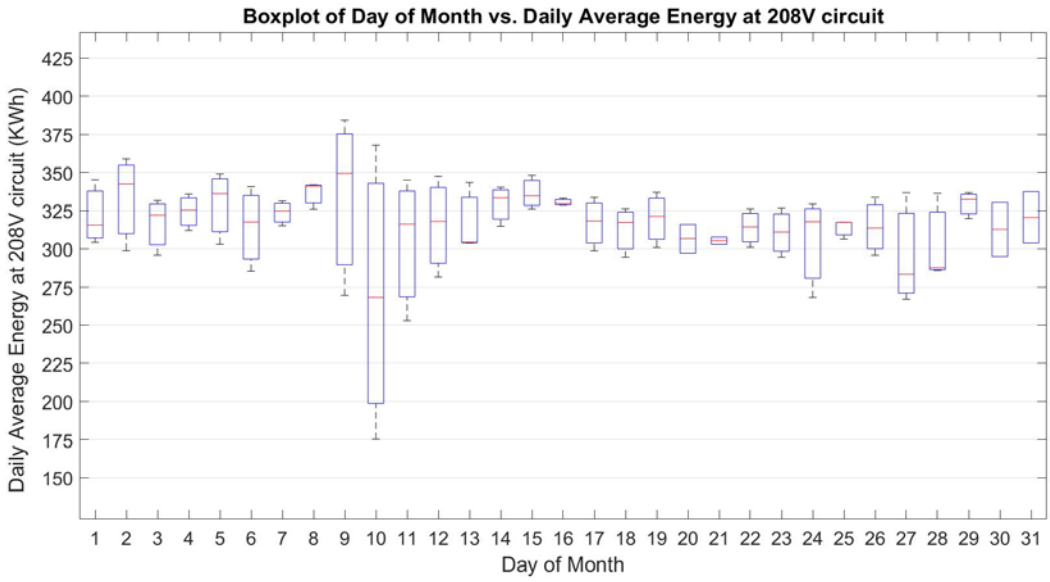


Figure 46 Day of Month vs. Daily Average Energy at 208V Circuit

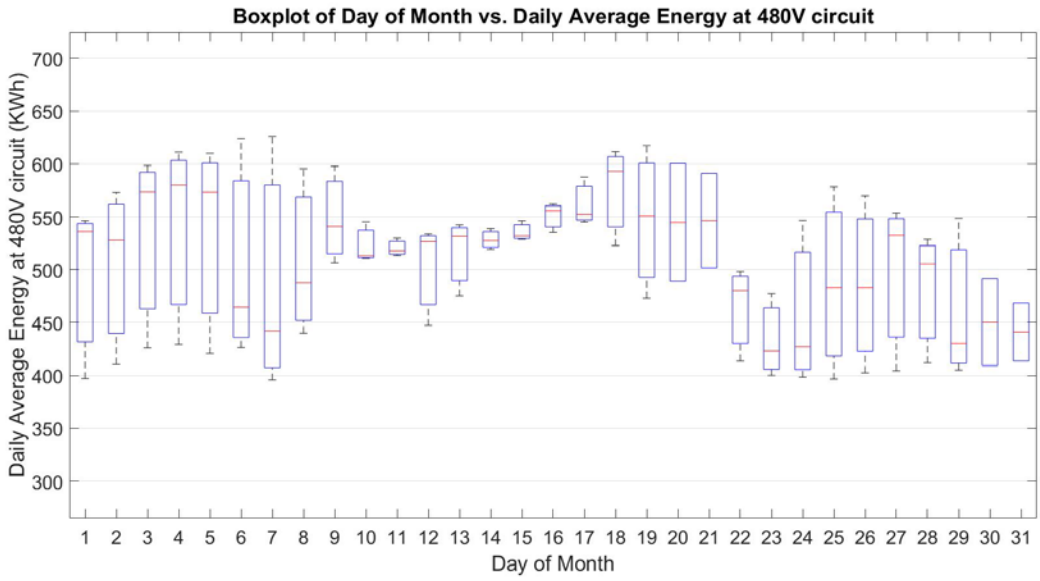


Figure 47 Day of Month vs. Daily Average Energy at 480V Circuit

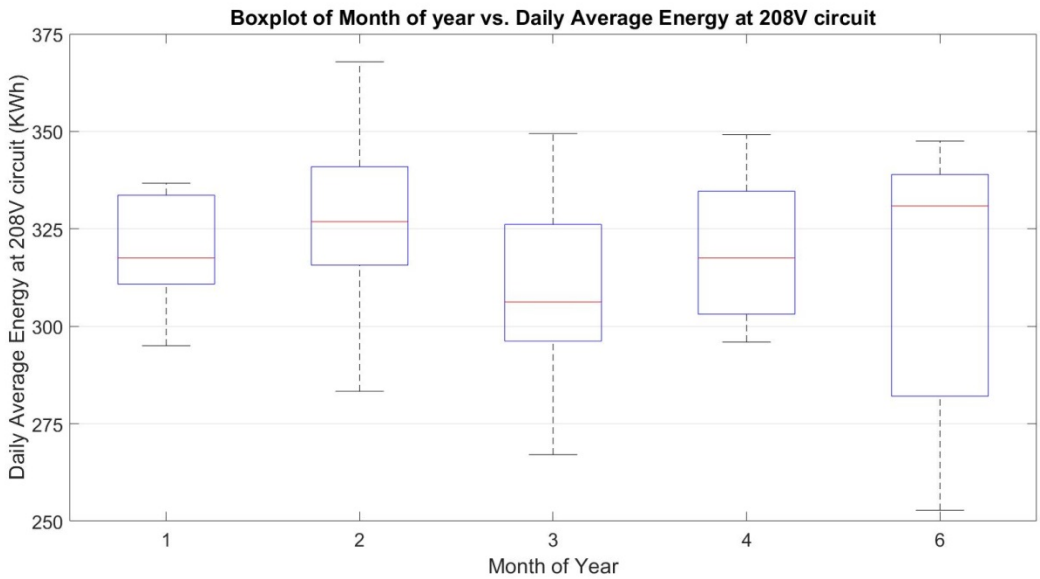


Figure 48 Month of year vs. Daily Average Energy at 208V Circuit

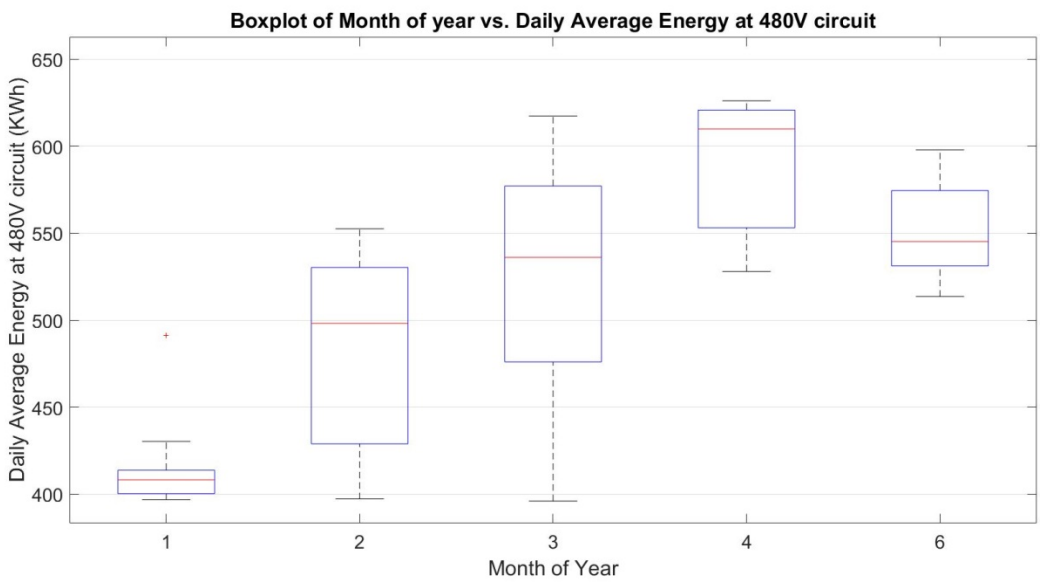


Figure 49 Month of year vs. Daily Average Energy at 480V Circuit

Building and Electrical Infrastructure Survey

and

Report on Loads and Trends

at

MCAGCC/MAGTFTC - Twentynine Palms, CA

By: Matthias Nikolakopulos, P.E.

For: GE Global Research

Contract: EW W912HQ-12-C-0002

Date: 10/27/16

Nikolakopulos, inc.
Electrical Engineering • Lighting Design

2780 SKYPARK DR. #280 · TORRANCE, CA · 90505
Tel: (310) 530-7277 · Fax: (310) 530-7283
www.nikolakopulos.com

Table of Contents

Mission	3
History	3
U.S. Military Bases	4
Housing/Demographics	5
Building Types	5
Electrical Infrastructure	6
Electrical Architecture	7
Alternate Energy	7
Capacity / Loads	8
Challenges	9
Tap Changers	10
Predicament	11
Microgrid	11
Conclusion	12
Appendix	13

Mission

The Marine Corps Base located in Twentynine Palms, CA - is officially known as the: Marine Corps Air Ground Combat Center (MCAGCC) / Marine Air Ground Task Force Training Command (MAGTFTC), and defines as its mission:

1) To manage the Marine Air Ground Task Force Training Program (MAGTFTP) and conduct service level Marine Air Ground Task Force (MAGTF) combined arms training to enhance the combat readiness of the operating forces and support the Marine Corps' responsibilities to national security.

2) To provide a standard of excellence in managing facilities, services and support to the operating forces, and families in order to ensure the readiness of the tenant and resident commands aboard the Combat Center.

History

The "Marine Corps Training Center, Twentynine Palms" was created in 1949. As the need for live-fire training grew along with the swelling ranks, the base grew in status, and was redesignated in 1953, and again in 1957 to "Marine Corps Base, Twentynine Palms".

Originally manned by Marines from Camp Pendleton, the primary mission was to prepare the new base for the arrival of permanent personnel. In 1952, the base conducted the first large-scale, live-fire field exercise - giving the Marines a glimpse into the facility's potential, and foreshadowing the large-scale combined arms exercises for which it is now known.

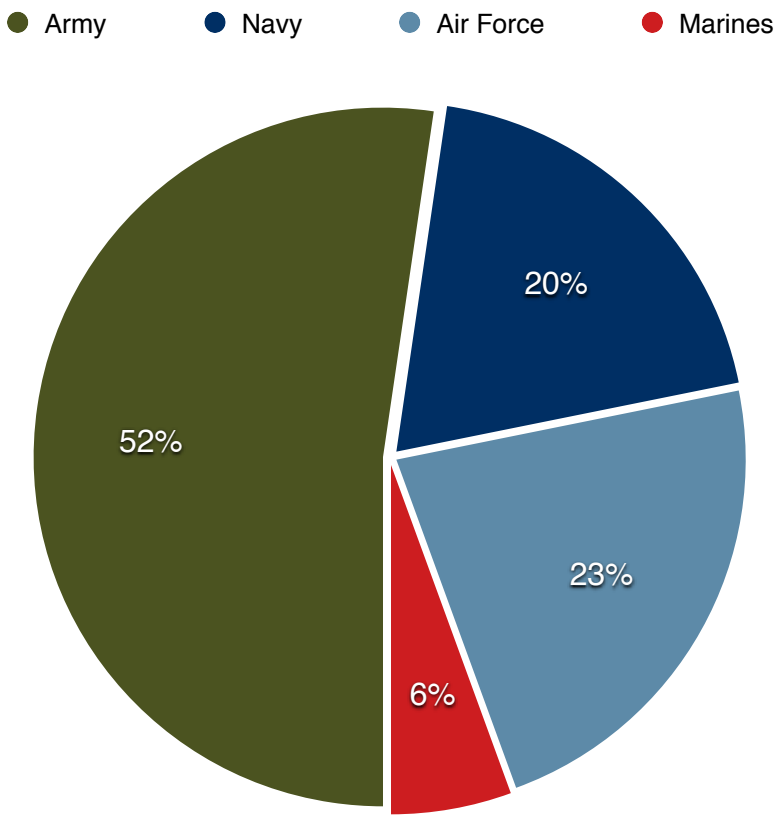
In 1976, an expeditionary airfield was added to the base's growing infrastructure. In 1978, the air-ground capability was complete; the name changed to "Marine Corps Air Ground Combat Training Center", and again in 1979 to its current "Marine Corps Air Ground Combat Center". Plans for the combined arms exercises were conceived - remarkable in two respects: the practice of combined arms, and live-fire and movement during the exercises that were unprecedented in scale. With the creation of a Tactical Exercise Control Center to control, instruct and critique the exercises, Twentynine Palms came to be known as a "permanent 'combined-arms exercise college' for all of the Marine Corps".

In 2000, the command was redesignated as "Marine Corps Air Ground Task Force Training Command". The base is currently home to one of the largest military training areas in the nation - with a total coverage of more than 1,100 square miles. And in 2008, the Marine Corps submitted for another 659 square miles - under the Grow the Force (GTF) program.

U.S. Military Bases

There are currently (323) military installations throughout the U.S. and its territories. Breakdown by branch is as follows:

- Army: (169) bases in (52) states and U.S. territories
- Navy: (63) bases in (25) states and U.S. territories
- Air Force: (73) bases in (40) states and U.S. territories
- Marines: (18) bases in (9) states and U.S. territories



Although small in number, Marine Corps bases perhaps best exemplify overall energy use profiles - as they combine fixed and mobile forces, heavy air and land-use exercises of all types, multiple classroom and training facilities, rapid deployment, and large permanent, as well as visiting personnel: thus providing good candidates to study building diversity and the associated electrical infrastructure - to glean insights into electrical loads and trends.

Given the shear size of Twentynine Palms, the depth and breadth of its buildings, training types, land and air exercise capabilities, as well as the large number of both resident and visiting personnel, the MCAGCC/MAGTFTC provides an especially good model to study.

Housing/Demographics

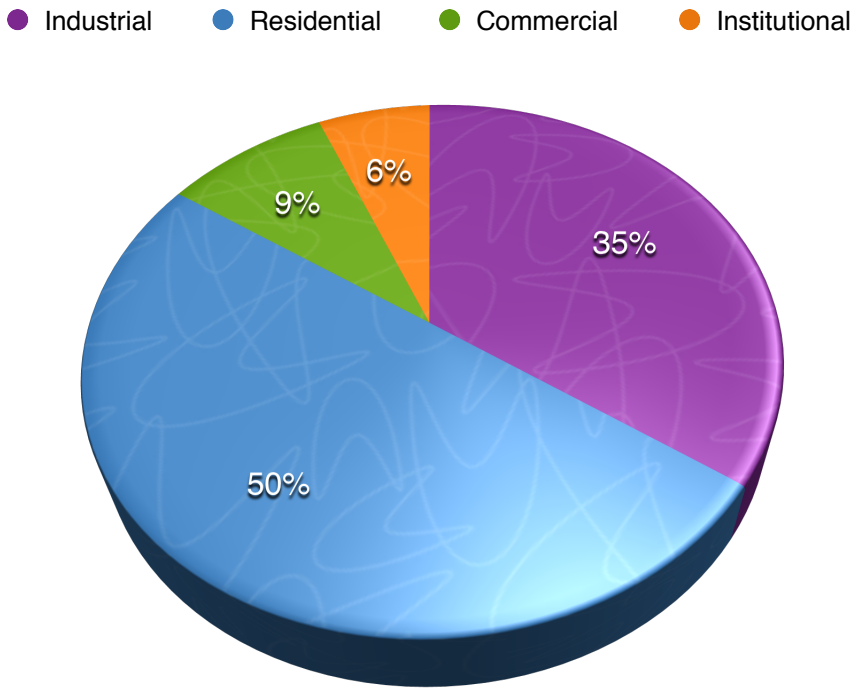
The main cantonment area ("Mainside"), which includes several BEQ's, has a total area of ~2 square miles. In the last census (2000) the total population was 14,090. With the (9) residential housing areas outside of Mainside; to the north: Fairway Heights and Ocotillo Heights, and south: Adobe Flats, Condor Terrace, Desert View Terrace, Joshua Heights, Marine Palms, Shadow Mountain and Sunflower Terrace, the population is now >25,000:

- 12,500 active duty
- 11,700 family members
- 1,400 civilians

Building Types

At over 650,000 acres, the MCAGCC/MAGTFTC is the largest U.S. military base by area in the world; however, its population is only one-tenth that of the largest bases in the nation. Though its population is modest compared to other large bases in the U.S., its panoply of buildings is not. The MCAGCC has over 1,625 buildings, categorized by (4) major types:

- Residential (820): BEQ's, duplexes, SFR's, multi-family, hotel
- Industrial (560): maintenance, storage, tank yards, warehouses
- Commercial (145): offices, hospital, MCX, commissary, theatre, parking structures
- Institutional (101): chapels, classrooms, library, schools, mess halls, gymnasiums



Electrical Infrastructure

Utility service to the base is provided by S.C.E. via 115kV O/H pole lines from High Desert station to their new Leatherneck substation - located on the northwest end of Mainside. It is configured with (3) 28MVA 115/34.5kV-YΔ transformers. One serves circuit (OS3501); the other two are paralleled and feed the other two circuits (OS3502 and OS3503).

These three 34.5kV circuits feed the Ocotillo Switching Station (OSS) located nearby - which constitutes the point-of-service, and provides a means of metering, monitoring, and switching the incoming feeds, as well as controlling minimum import and export power.

From OSS, the three 34.5kV lines travel east and go around Mainside in a circular fashion - covering it with primary loop feeds. OS3501 turns south and covers the west and south sides of Mainside. OS3502 heads east through Mainside, cover its entire east side. OS3503 turns north at Mainside to cover its north end, and then also heads north to Camp Wilson airfield, and CAMOUT substation: the only two areas with a radial feed.

The primary loops feed thirteen 34.5/12.47kV-ΔY substations of varying sizes, as follows:

- “AA”: (3) 7MVA - located center east Mainside
- “Adobe Flats”: 7MVA - located southwest of Mainside
- “CAMOUT”: 5MVA - located ~10 mi. north of Mainside
- “Camp Wilson”: 5MVA - located ~5 mi. north of Mainside
- “Del Valle”: 5MVA - located north Mainside
- “EE”: 6MVA - located northwest Mainside
- “Fairway Heights”: 3MVA - located northwest of Mainside
- “Gillespie”: 7MVA - located northeast Mainside
- “Joshua Heights A”: 7MVA - located southeast of Mainside
- “Joshua Heights B”: 5MVA - located southeast of Mainside
- “N1” (North): 5MVA - located south Mainside
- “N2” (South): 5MVA - located south Mainside
- “Ocotillo Heights”: 3MVA - located northwest of Mainside

These substations feed transformers for specific buildings or loads. Most buildings have 12.47kV 3⌀ pad-mounts with 480V or 208V secondaries, from 25 to 2500kVA. Smaller 1⌀ or 3⌀ loads are fed by pole-mounted transformers, from 25 to 100kVA. Residential areas are served by 12.47/240-120V 1⌀ “clam-shell” style pad-mounts (generally 167kVA).

Electrical Architecture

The primary loops covering Mainside can be reconfigured through various SCADA-Mate switches to re-route and/or reconfigure the primary to feed the substations from alternate directions and/or circuits - providing both physical and electrical redundancy.

In the event of a physical disturbance (e.g., O/H line down, pole break, trenching incursion, etc.), a substation can often be fed from the same primary circuit via an alternate path, while sectionalizing to isolate the area of disturbance - facilitating uptime, and repair.

If one of the three primary circuits from OSS is lost, 34.5kV can generally be re-routed from another available circuit to pick up critical load, while additional switching/sectionalizing can shed less critical loads off of that circuit as needed - maintaining and prioritizing loads.

Additionally, though some remote substations feed only specific areas (e.g., Camp Wilson and CAMOUT), the others near Mainside feed into multiple connected 12.47kV secondary loops that can be configured by SCADA-Mate switches to provide necessary redundancy. That is, the 12.47kV secondary grid was designed using “7-segment display” type architecture - to facilitate bi-directional switching scenarios for both types of occurrences.

Thus, most areas throughout Mainside can be fed from one or more directions, and/or circuits - from any number of substations: providing maximum flexibility and reliability. Furthermore, even substations with radial feeds (which cannot then be back-fed from another direction) can still take advantage of the ability to parallel circuits - and maintain load in a given area. This is especially true in the residential areas outside of Mainside. Lastly, all substations employ multiple feeds into the loads, oversize C/B’s and conductors, redundant conduit, backup SEL digital relays and UPS power, and remote monitoring.

Alternate Energy

In addition to a flexible electrical grid, the base employs ~17MW of alternate power, along with ~9MW of sustainable power, in many different types, sizes and capacities, as follows:

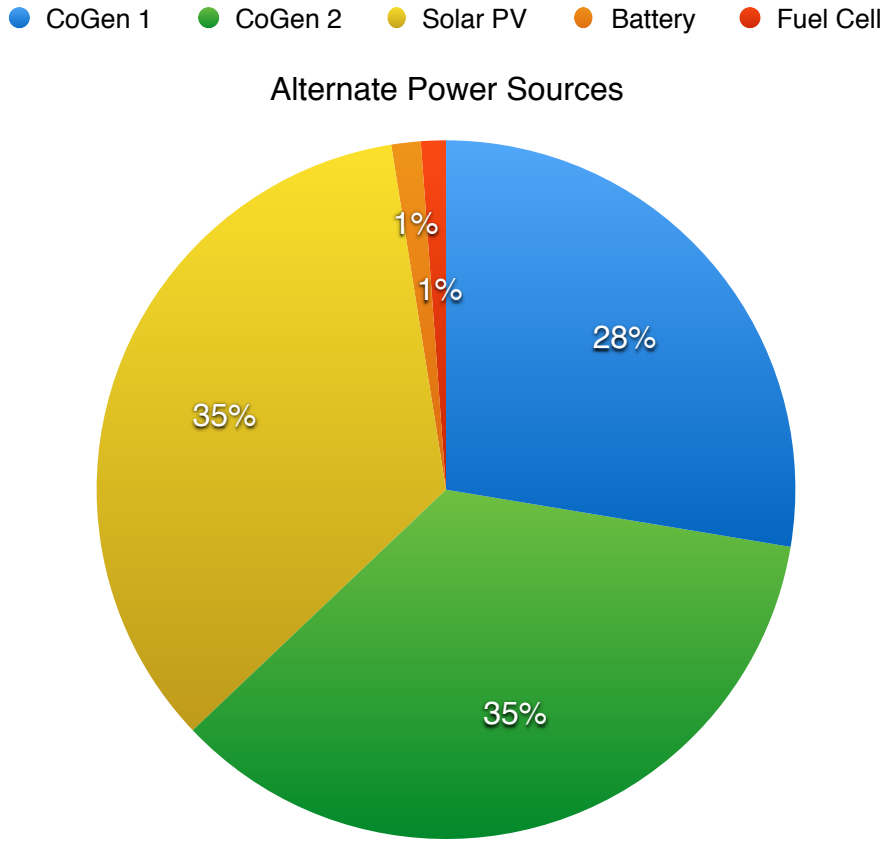
- Cogen Plant #1 B1579: 7.2MW gas-fired turbine at Substation “AA”
- Cogen Plant #2 B1991: (2) 4.6MW gas-fired turbines at “Gillespie” Substation
- 300kW fuel cell at Substation “AA”
- PPA: 1.015MW solar photovoltaic field
- 354kW battery farm
- (56) additional PV arrays, ranging from 13kW to 1.2MW - totaling 8MW
- Multiple diesel generators, ranging in size from 50kW to 1.5MW (paralleled)

Capacity / Loads

The capacity of the S.C.E. Leatherneck substation is (3) x 28MVA transformers = 84MVA. This is also equivalent to the total capacity of the thirteen substations throughout the base.

Loads have grown steadily at the base - generally commensurate with the population. Typical base-wide summertime loads can now get up to 21-22MW. Wintertime loads are approximately one-half of that (~10-11MW). With a total cogeneration capacity of ~16MW, the base should easily be able to island 24-7 during winter. Even with only one of the two Gillespie (CoGen 2) 4.6MW turbines running, the output is still sufficient: 11.8MW.

During summer, as long as both cogen plants are fully functioning, the base should still be able to island - as long as at least one-half of the solar PV arrays are producing. At night, modest load shedding can easily maintain all critical loads until the PV comes back up.



Once the new Microgrid is up and running, the base should be able to function fairly autonomously, and with controls and metering could even instigate new import/export agreements with the Utility. Instead of the current minimum import agreement (under Rule 21), the base could even enter into a sustainable energy (i.e., solar PV) export agreement - whereby superfluous green energy produced would be compensated, rather than wasted.

Challenges

The overall capacity, quality, and stability of the 34.5kV grid has increased in recent years - due to the new S.C.E. High Desert service line feeding the new Leatherneck Substation. Whereas the 34.5kV primary grid was formerly carrying voltages closer to 33kV - causing many problems, and amplifying the impact of high overall loading, large motor starting, multiple co-gen and other sources coming on and off line, etc., the additional 84MVA now mitigates the problems of utility voltage sags, swings, and weather-related temperament.

But even as the incoming utility has largely been stabilized, our AVR research over the past year at the base has still shed light into the advantages of automatic tap-changing on the secondary (building) side - to adjust and compensate for various load types and demands, as well as for the multiple, and sizable, alternate power sources coming on and off-line.

Obviously, the desire is to make as effective use as possible with these alternate sources. But with up to (6) different types and sources of alternate power, including (57) separate PV arrays, as well as infinite switching scenarios - bringing any and all of the above on and off-line at any given moment - voltage swings can still wreak havoc on the primary line: affecting building loads' output, efficiency, and longevity. The stabilized utility is mitigated.

This will be exacerbated by the new Microgrid project, since the goal is to allow the base to take maximum advantage of its multiple sources, even going fully-islanded as necessary in the event of a loss of utility. It will entail various switching schemes and control scenarios (including some that will be automated) to ensure maximum uptime, and green power production, in all situations; albeit with a power quality that may suffer.

Thus, it would be desirous to automatically adjust serving voltage to buildings throughout the base - compensating for the secondary MV swings. However, adding a full-size kVA AVR is cost-prohibitive. But if the SCR-driven automatic tap-changing system within an AVR could somehow be adapted into an existing service transformer, that would be ideal. The problem lies not in technology, ironically, but more in terms of space, cost and safety.

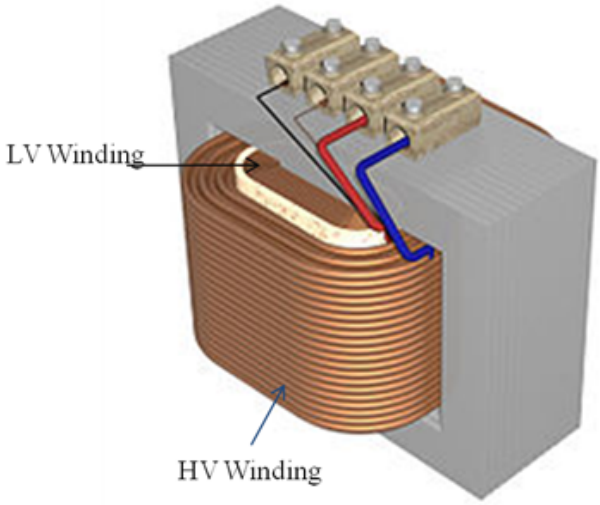
That is, 3⌀ pad-mount serving transformers generally have the space for such a device, but only offer tap-changing on the primary (MV) side: not safe, practical, or cost-effective. 1⌀ clamshell transformers would not have space. Distribution transformers can certainly be easily tap-changed, but many buildings do not have them (as their loads are single voltage), and those that do could then only offer voltage adjustment on the secondary side (greatly limiting the benefits). Also, they may or may not have the requisite space inside.

Tap Changers

A transformer tap changer is typically placed on the high voltage side (primary) because:

1) The HV winding is generally wound over the LV winding; hence, it is easier to access the HV winding turns vs. the LV winding turns.

2) Because of the higher voltage, the current through the HV winding is less compared to the LV windings; hence, there is less "wear" on the tap changer contacts. Due to the lower current through the load tap changer, the changeover spark energy is less.



Although transformers can have de-energized tap changers (DETCs), aka: no-load tap changers (NLTCs), their purpose is simply to help match the voltage to the equipment needs. If the incoming voltage increases or decreases, and remains at this level for an extended period (weeks or months), one can change the tap setting of the DETC.

Most DETC designs center around a five-step switch. Usually, the device affects the number of windings on the primary side of the transformer, with two 2.5% taps above and below the nominal voltage: because the American National Standards Institute (ANSI) dictates that a Utility supply a voltage that will not vary by more than 5% from nominal.

However, operation of a DETC must happen only under a de-energized condition; otherwise, an internal arc can occur that will affect the internal components of the transformer and create a safety hazard for personnel. This makes it impractical for our application. They are not used to compensate for a short-term fluctuation in voltage, and they are not automatic. Note that DETC's also require maintenance.

Predicament

Utility comes in at 34.5kV - feeding the substation primaries. However, on-site generation occurs at 12.47kV, and thus feeds into the secondary grid (and/or back up through the substation transformers into the primary grid). Either way, it is a MV grid that is fluctuating, and thus cannot be easily (or cost-effectively) controlled. This precludes the option of a tap-changing system at the substation level (which would be the most efficient).

Therefore, the ultimate candidate to have an automatic tap-changing mechanism would be the pad-mount transformers serving the multitude of buildings and loads on the base. Unfortunately, these pad-mounted transformers have their tap-changing capability only through fixed, manual taps on the primary (MV) side: impractical and cost-prohibitive.

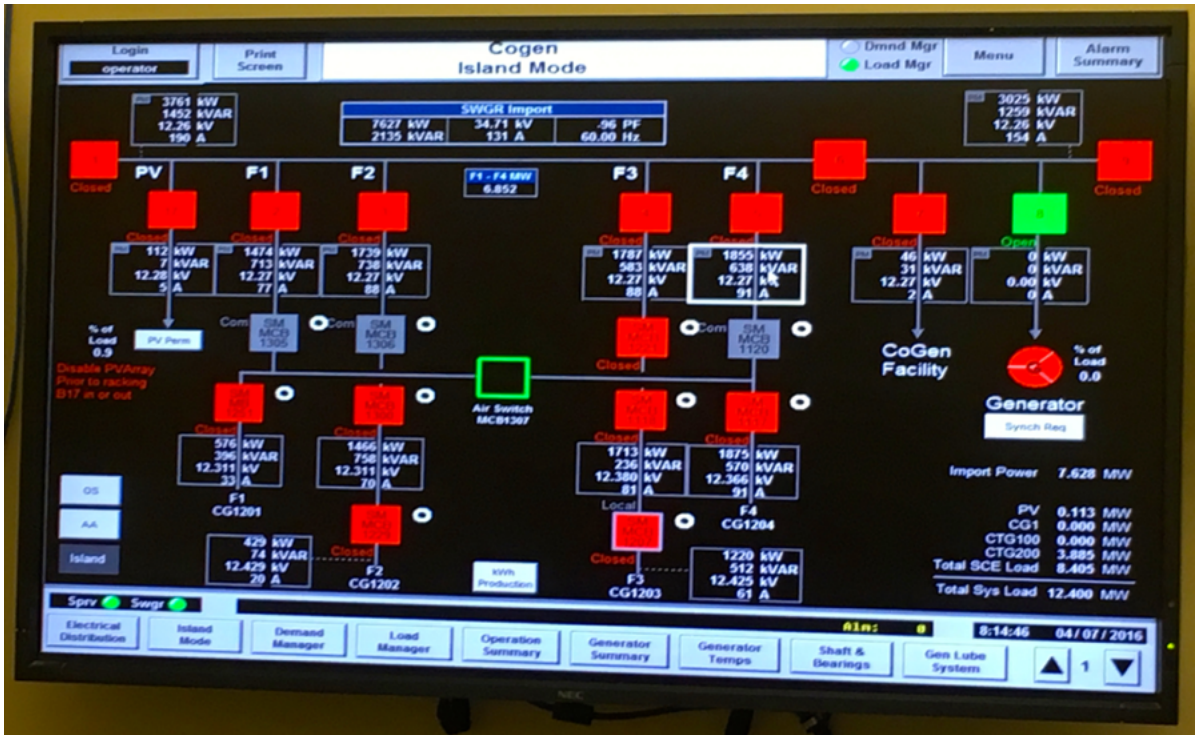
Therefore, we must go down to a more granular level. The voltage stabilization and/or adjustment must come at the building service; i.e., from the pad-mount secondaries (480/208/240V). Unfortunately, this means the installation of a full kVA-rated AVR. Although this is not practical - especially in an existing installation, the conclusion from the AVR project at the base this year was that the automatic SCR-driven tap-changing mechanism would be ideal - if only it could be retrofitted to existing building transformers.

For now, this leaves only building internal distribution transformers; i.e., 480/208-120V (to the extent they have them). These are routinely left at nominal - and can heretofore only have their taps changed manually, in a power-off condition: certainly not conducive to real-time adjustment. However, they would be good candidates for a retrofit of an automatic tap-changing system: they are LV, there is generally space inside, and there would be no need for transformer replacement. But the loads, and thus ROI, would be small.

Microgrid

The electrical loads on a military base are large, varied, and put enormous demands on the infrastructure. As more and more alternate sources of power are coming online, the utility grids are not prepared to handle the enormous swings. Battery farms are still way too expensive to provide viable input and stabilization. In order to take maximum advantage of the CHP's and PV solar arrays that are being installed, there must be a way to stabilize the voltage - allowing a mixed bag of sources to work harmoniously together and serve loads.

With the Microgrid project bringing all of the pieces together using a comprehensive HMI, there's no better time to envision all methods of control - to ensure optimal success.



CoGen Plant #2 HMI

Conclusion

The promise of automatic tap-changing is readily apparent; the issue is being able to add this feature to existing transformers. Unfortunately, there are no good options at the present time, other than building level internal distribution transformers - which will only allow voltage adjustment at the smallest levels (i.e., only 208V loads). Until AVR technology is built into MV service-sized pad-mounts, there may not be a viable solution.

Nevertheless, we should keep plugging away. This is a promising, and yet untapped idea to save energy, increase reliability, and prolong equipment life - saving time and money. A solution would parlay the countless dollars and man-hours being spent on alternate energy - making it much more practical. In short, the ideal would be to have electrical loads fed from any number of sources, at any given time, and not know the difference.

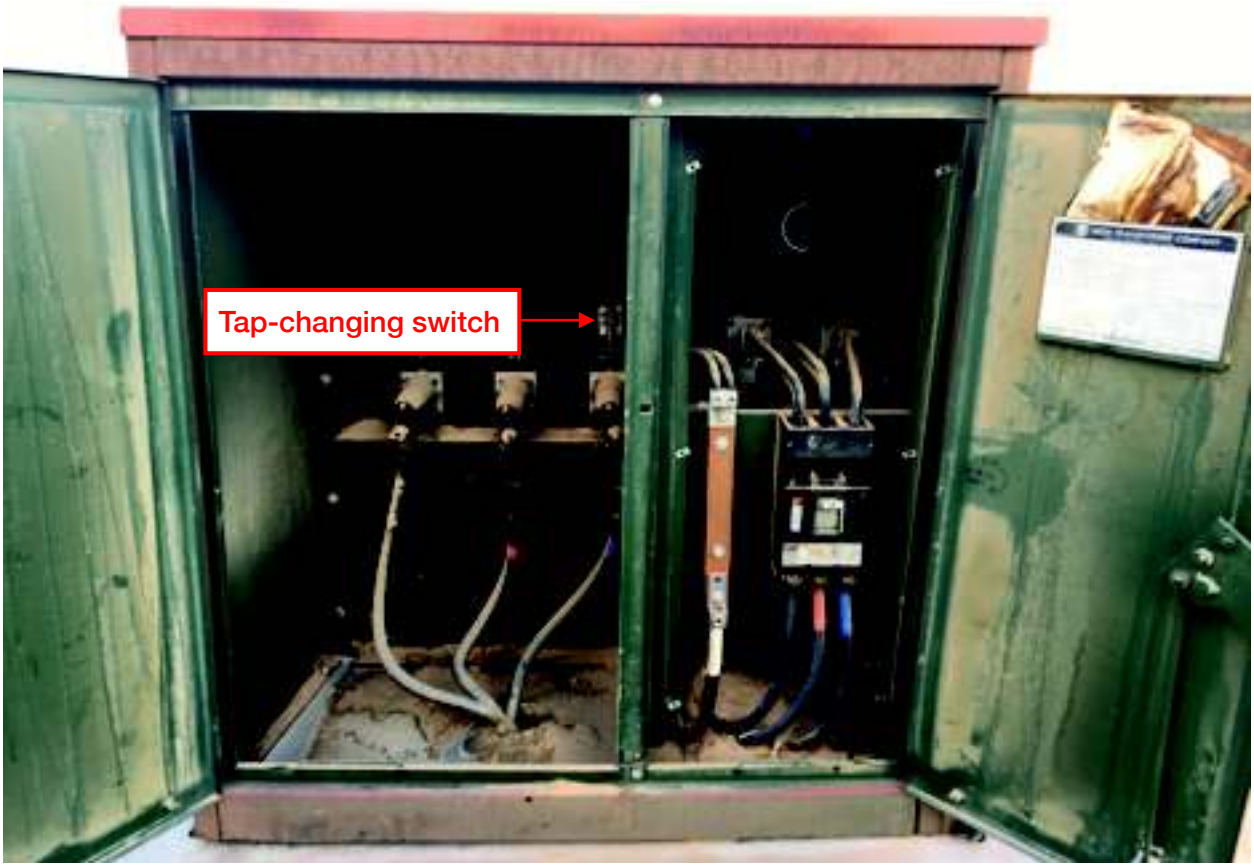
It remains to be seen how automatic tap-changing and other emerging technologies can weave their way into military installations throughout the country. The ultimate goals should be: to maximize on-site green production, return superfluous power to the grid, serve and maintain loads - all while saving time, money and conserving resources.

The MCAGCC/MAGTFTC is a large, varied, technology-rich environment with a panoply of electrical loads and sources, and a sophisticated infrastructure making it the ideal test bed. With personnel that are ready, willing and able to explore all current and future methods of electrical energy production, distribution, and control, Twentynine Palms remains an ideal candidate to lead the way in making power safer, more reliable and more economical.

Appendix

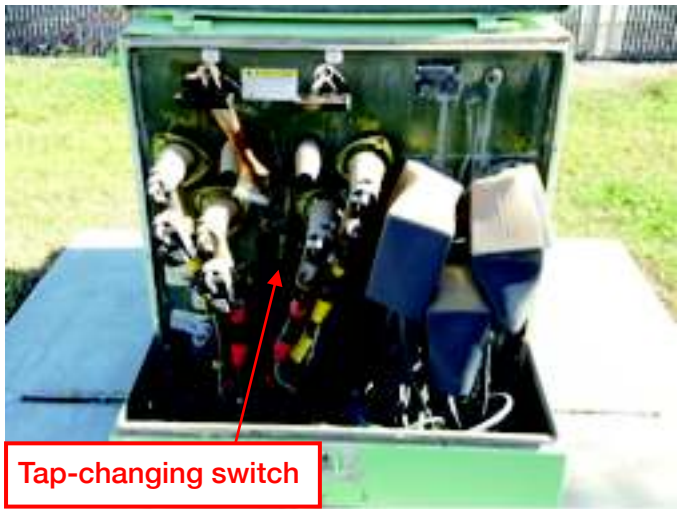
Pad-Mount Transformer (12.47kV/480V-3∅)

Typical MV/LV Bldg. Service Transformer



Clamshell Transformer (12.47kV/240V-1∅)

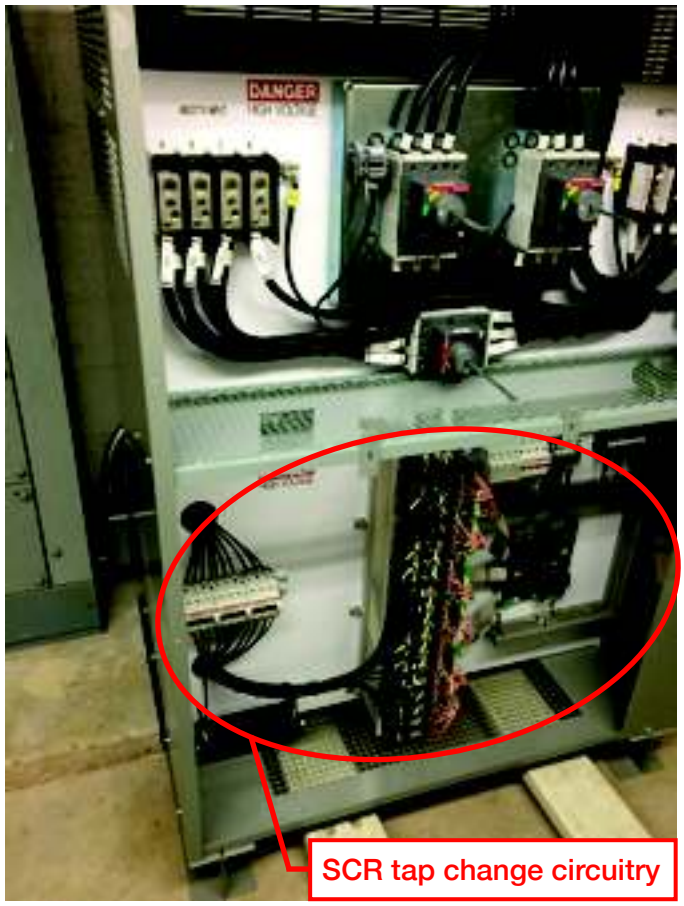
Typical Residential Transformer



(No spare internal space)

LV Distribution Transformer (480/208V-3∅) / AVR (480V-3∅)

Typical LV distribution transformer



AVR control circuitry: a fraction of the overall size

Residential

Typical BEQ's

Marine Regiment BEQ

Base Hotel

Officer Single Family Residence

Typical Duplex Housing

Industrial

Large Auto Repair Building

Radar Testing Facility

Center Magazine Area (Munitions Depot)

Artillery Yard and Repair

Tank Yard and Repair

Large Storage Warehouse

Commercial

Large Marine Corps Exchange

Naval Hospital

Commissary

Marine Battalion HQ (LEED Gold)

Movie Theatre

G-6 Communications HQ

Institutional

Community Center

Catholic Chapel

Mess Hall

Elementary School

Library

Education Center

Substations (34.5kV/12.47kV-3∅)

"AA"

"Adobe Flats"

"Camp Wilson"

"Del Valle"

"EE"

"Fairway Heights"

Substations (cont.)

"Gillespie"

"Joshua Heights A & B"

"N1 and N2"

"Ocotillo Heights"

"Ocotillo Switching Station"

SCE "Leatherneck"

Various Power Sources

CoGen Plant #1

CoGen Plant #2

Building-mounted PV Solar Array

1.2MW PV Solar Farm

Diesel backup generator

300kW Fuel Cell