Title
Field Demonstration of One-Cycle Control Active Power Filter (OCC-APF)

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FINAL PROJECT REPORT

FIELD DEMONSTRATION OF ONE-CYCLE CONTROL ACTIVE POWER FILTER (OCC-APF)

Prepared for: California Energy Commission

Prepared by: One-Cycle Control, Inc.

One-Cycle Control, Inc.

The Art of Power Processing

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One-Cycle Control, Inc. (OCC) worked in collaboration with Demonstration Site Coordinators to achieve the results reported here. The OCC team acknowledges the support of the following organizations and people in the performance of this field demonstration program.

Ron Meyer, Larry Patterson, Chad Shinkle of the Santa Margarita Water District (SMWD)

Paul Wingco, Chris Abamonto of the University of California, Irvine (UCI)

David Zomorrodian of Pacific Transformer (PT)

PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Field Demonstration of One-Cycle Control Active Power Filter is the final report for the *Field Demonstration of One-Cycle Control Active Power Filter* project (contract number CEC-500-02-004 MR-075) conducted by One-Cycle Control, Inc. The information from this project contributes to PIER's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

Electric power networks (utility, industrial facility, etc.) deliver power that was generated with sinusoidal voltage waveforms. When load currents are sinusoidal and in phase with the voltage, power networks operate at the peak efficiency, the maximum available capacity, and the greatest stability. However, most electronic loads draw non-sinusoidal currents and reactive currents, diminishing power-network efficiency, stability, and capacity. This coupled with rapid growth in power demand pushes the operating margin to the limit, often resulting in instability, inadvertent shut-down, and economic loss.

OCC, Inc. has developed OCC-APF products that cancel harmonics and reactive currents making “non-ideal” loads appear “ideal” to the power network. The OCC-APF is based on breakthrough technology featuring ~10x size reduction, ~5x weight reduction, and extremely rapid dynamic performance compared to typical. With small space requirement, low user interface burden, and high-reliability, OCC-APFs deliver system-wide benefits to facilities and utilities, potentially relieving congestion caused by reactive currents, reducing peak kVA demand, improving power-network efficiency, and raising the system reliability.

During this project period, OCC, Inc. performed field demonstration of a 480 Vac 50 Amp (~40 kVA) OCC-APF at the Santa Margarita Water District Monterey Villa pumping station to improve the power quality. The the installation of OCC-APF in the field has resulted in ~21 percent reduction in line kVA.

Electricity customers limited by capacity constraints in their existing facility transformer(s) or power distribution network can utilize the OCC-APF to relieve congestion caused by reactive current and enable load growth on the existing infrastructure. Customers who are faced with high penalties for poor power factor or are charged based on kVA rather than kW may also achieve cost savings and measurable return on investment through the use of an OCC-APF. An assessment of the facility capacity constraints and electricity rate structure can quickly lead to a determination of the measurable benefits of OCC-APF deployment.

Keywords: California Energy Commission, One-Cycle Control, Active Power Filter, APF, Power Quality, Power Factor, Harmonics, Transformer Efficiency

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Introduction

Electric power networks (utility, industrial facility, etc.) deliver power that was generated with sinusoidal voltage waveforms. When load currents are sinusoidal and in phase with the voltage, power networks operate at the peak efficiency, the maximum available capacity, and the greatest stability. However, most electronic loads draw non-sinusoidal currents and reactive currents, diminishing power-network efficiency, stability, and capacity. This coupled with the rapid growth in power demand pushes the operating margin to the limit, often resulting in instability, inadvertent shutdown, and economic loss.

OCC, Inc. has developed OCC-APF products that cancel harmonics and reactive currents making “non-ideal” loads appear “ideal” to the power network. The OCC-APF is based on breakthrough technology featuring ~10x size reduction, ~5x weight reduction, and extremely rapid dynamic performance compared to the state of the art. With small space requirement, low user interface burden, and high-reliability, OCC-APFs deliver system-wide benefits to facilities and utilities, potentially relieving congestion caused by reactive current, reducing peak kVA demand, improving power-network efficiency, and raising the system reliability.

Demonstration Sites

Initially three sites were considered for the field demonstration: UC Irvine (UCI), Pacific Transformer (PT), and Santa Margarita Water District (SMWD). The site survey revealed that the accessible line voltage at UCI and PT (208Vac 3-phase) was different from SMWD (480Vac 3-phase). Among the three-sites, SMWD offers the most challenging load profile: large water pumps with extremely high inrush current and it was the most representative of the expected OCC-APF usage in Industrial and Water applications, thus it was selected as the first demonstration site. The team had planned to develop a 208Vac 3-phase OCC-APF to demonstrate at the other two sites. However, the development and field testing of two high-power converter products with different voltage rating is both time and capital prohibitive. With extensive comparison and consideration as well as consensus with the CEC program manager, the team decided to focus its effort on the 480Vac OCC-APF for the entire program to ensure a solid successful outcome.

Conclusions

The development and field demonstration of the OCC-APF has been a successful endeavor. Demonstration at the SMWD site enhanced the OCC-APF development, since the loads at this site are very dynamic with startup inrush current of 600Amps. This enabled the OCC team to aggressively test and improve the performance of the OCC-APF over several cycles of assessment and design modification. The result is a robust field-tested OCC-APF that is ready for commercial sale. As of this report writing, the OCC-APF has passed applicable UL requirements and OCC is preparing for the first commercial sale.

Electricity customers limited by capacity constraints in their existing facility transformer(s) or power distribution network can utilize the OCC-APF to relieve congestion caused by reactive current and enable load growth on the existing infrastructure. Customers who are faced with high penalties for poor power factor or are charged based on kVA rather than kW may also achieve cost savings and measurable return on investment through the use of an OCC-APF. An assessment of the facility capacity constraints and electricity rate structure can quickly lead to a determination of the measurable benefits of OCC-APF deployment.

CHAPTER 1: OCC Active Power Filter (OCC-APF)

Breakthrough OCC Technology and Products

One-Cycle Control (OCC) technology was invented at Caltech, developed, improved, and systematically applied to numerous power converter applications by the inventor Prof. Keyue M. Smedley and her team at the UC Irvine Power Electronics Lab. In 2004, OCC Inc. initiated the productization and commercialization of the OCC technology. Since its establishment, the OCC team has won numerous government contracts from the Department of Energy (DOE), Department of Defense (DOD), and the California Energy Commission/California Institute for Energy and Environment to develop the OCC power converter architecture. In addition, the OCC team has secured numerous private contracts that have enabled further refinement of the architecture and expansion of the range of applications to serve the renewable/alternative energy, aerospace, and advanced transportation markets.

History of OCC-APF

In 2000 the UC Irvine Power Electronics Lab (UCI PEL) demonstrated the first three-phase OCC-APF proof-of-concept prototype. The technology gained further development to a 5kVA prototype under a PIER EISG grant **(Smedley, K. 2005)** and was expanded to enable combined APF and STATCOM functions under a second PIER EISG grant **(Smedley, K. 2007)**. In 2007, OCC Inc. developed a Grid-Tied Inverter (GTI) with the APF function to enable delivery of power to the grid while also correcting the power factor and harmonics caused by facility loads **(Smedley, G. 2009)**. Each PIER EISG program contributed to the knowledge essential for the success of this OCC-APF field demonstration.

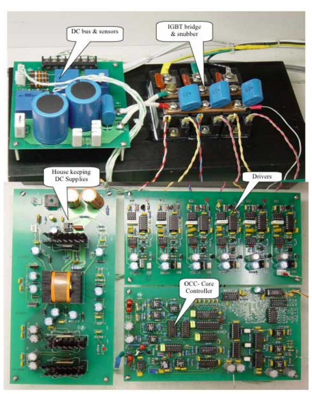


Figure 1: UCI EISG OCC-APF (left); OCC-APF for PIER Field Demonstration (right)

Photo Credits: UCI PEL (left); G. Smedley, OCC (right)

Demonstration OCC-APF

During this PIER Field Demonstration program, the OCC team designed, commissioned, and field tested a viable commercial OCC-APF (Figure 1 (right)) with a 50 Amp, 480 Vac 3-phase rating (~40 kVA). A brochure for the commercial product is included in Appendix A. The field demonstration site provided an extreme test for the OCC-APF that resulted in significant design improvements. Of the original three sites, the SMWD site proved to be the best testing ground and has helped enable the creation of a robust high-performance OCC-APF product. As of the writing of this final report, the OCC team has completed relevant UL safety testing with a third-party independent testing lab, so the OCC-APF is ready for commercial sale.

CHAPTER 2:
Field Demonstration Sites

Initially three sites were considered for the field demonstration: UC Irvine (UCI), Pacific Transformer (PT), and Santa Margarita Water District (SMWD). The site survey revealed that the accessible line voltage at UCI and PT (208Vac 3-phase) was different from SMWD (480Vac 3-phase). Among the three-sites, SMWD offers the most challenging load profile: large water pumps with extremely high inrush current and it was the most representative of the expected OCC-APF usage in Industrial and Water applications, thus it was selected as the first demonstration site. The team had planned to develop a 208Vac 3-phase OCC-APF to demonstrate at the other two sites. However, the development and field testing of two high-power converter products with different voltage rating is both time and capital prohibitive. With extensive comparison and consideration as well as consensus with CEC program manager, the team decided to focus it effort on the 480Vac OCC-APF for the entire program to ensure a solid successful outcome.

UC Irvine Site – Engineering Lecture Hall Building

The UCI site includes 129 transformers in the primary-level distribution. OCC created a population distribution of the transformers (Figure 2) based on provided data. To identify candidate transformers for a demonstration site, two basic assumptions were made: (1) maximum transformer loading at 80 percent of rating and (2) OCC-APF rating is 1/3 of the maximum load. With these two assumptions, the field of candidates was narrowed to eleven (11) transformers with kVA rating less than or equal to 150kVA. With load-criticality as an additional selection criterion, the number of candidates was further reduced to five. The five were further reduced to three candidates when the presence of metering on the low-voltage side was considered; following further analysis is was determined that shutdown to install the APF at these sites would not be convenient.

The search was expanded to include transformers with larger kVA ratings, resulting in the selection of a 225kVA transformer at the Engineering Lecture Hall. Historical data showed a 24 kW peak with 15 percent THD and a power factor of 0.83. The APF can provide advantage here by canceling the harmonic current and correcting the power factor; furthermore, the building is very representative of other campus buildings and has few logistical issues compared to buildings that support offices for personnel and/or computers.

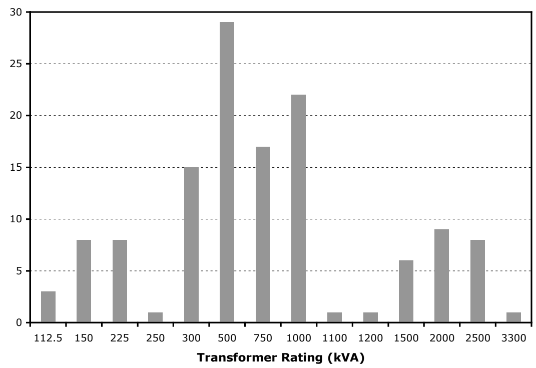


Figure 2: UCI transformer population distribution (left) and Engineering Lecture Hall (right)

Photo Credit: G. Smedley, OCC

As the OCC-APF field demonstration project moved forward, access for metering the 12kV side of the transformer was not possible and ultimately the decision was made to apply the OCC-APF to a secondary transformer inside the building that stepped the 480Vac to 208Vac so that the two sides of the transformer could be measured. By this time, substantial development had already been completed on the 480Vac OCC-APF, so it was decided that this site would be done later in the project when OCC had developed a 208Vac version of the OCC-APF.

Although this site was representative of a building load profile, the magnitude of the loading was small and the dynamics were minor compared to the SMWD site. During the project, the original site coordinator (Paul Wingco) moved to another position and Chris Abamonto assumed the position. Ultimately, the SMWD site proved to be the best testing ground for the OCC-APF and the UCI test site was not utilized.

Pacific Transformer Site – Light-Duty Manufacturing

The site survey of Pacific Transformer included determination of grid configuration, grid component definition (e.g. transformer sizes), and load profiling. Figure 3 shows a schematic of the transformer sizes and general loads (left) and a photo of the facility (right). Transformer #1 serves the machine shop and office; since machine shop is rarely operating, this transformer is very lightly loaded. Transformer #2 serves heavier manufacturing loads. Transformer #3 serves a three-phase furnace at ~40kW; however, since a resistive load the current draw is expected to be quite clean.

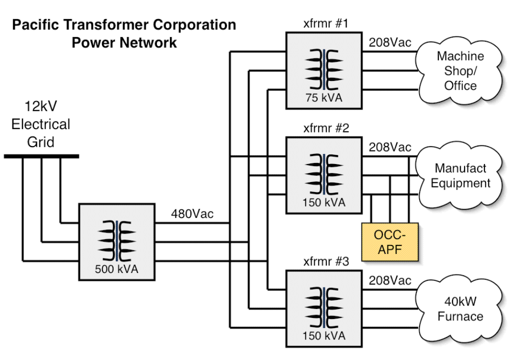


Figure 3: Pacific Transformer Grid Diagram and Building Photo

Photo Credits: Pacific Transformer, Inc. stock photo

The most desirable candidate for OCC-APF installation is therefore Transformer #2 since it serves manufacturing loads that include: single-phase and three-phase AC motors, single-phase DC motors, soldering irons, soldering pots, and HID lighting. During a survey visit the OCC team found load currents on the primary side of Transformer #2 were 42 Arms, 53 Arms, and 60 Arms. Clearly there was a significant imbalance caused by the presence of single-phase loads. The OCC team also made measurements of power quality using a Fluke Model 434 Power Quality Analyzer. The data showed that the majority of harmonic content is found in the 3rd and 5th harmonics. The percent THD at the input of the transformer is significantly higher than at the output of the transformer. This would seem to indicate that the transformer core is undersized and may be going into saturation. To conclude, the measurements indicated that the load on Transformer #2 is acceptable for this field demonstration program. However, due to the requirement for 208Vac 3-phase OCC-APF, this site was not used for the demonstration.

Santa Margarita Water District Site – Water Pumping Station

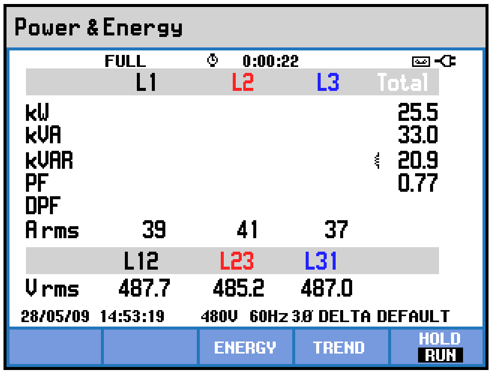
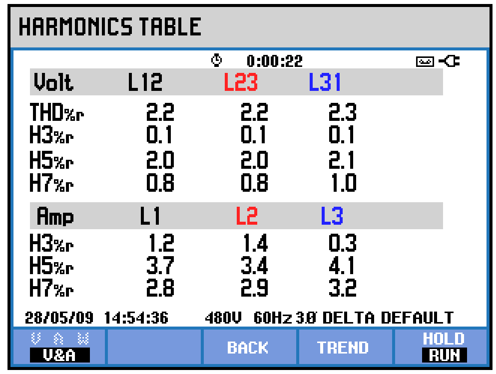
The Santa Margarita Water District (SMWD) has many pump loads of various sizes throughout their service territory. OCC worked with SMWD to conduct a preliminary assessment of 21 Domestic Pump Facilities, 9 Non-domestic Pump Facilities, and 17 Lift Stations that employ multiple pumps with individual horsepower ratings ranging from 10 to 500 HP (7.5 to 373 kW). Of these various facilities, the Non-Domestic Pump Facilities were determined to be the least critical, and of the 9 possible facilities two were identified with pump loads within the desired range for this APF field-demonstration program. Site A (Monterey Villa) employs three underground pumps rated at 10, 30, and 30 HP and Site B (Prima Descheca) employs a 40 HP pump. Following visits to the sites, the Monterey Villa site (Figure 4) was selected due to proximity to OCC and the multiple-pump loads that were expected to provide greater dynamics. Ultimately, the OCC and SMWD teams worked together to mount the OCC-APF in an external enclosure, (approx: 30" x 24" x 8") on the right side of the input power cabinet (Figure 4 (right)).

Figure 4: SMWD Site showing mounting location (left) and installed OCC-APF (right)

Photo Credits: G. Smedley, OCC

Measurements taken at the site (Table 1) show that most harmonic content is found in the 5th and 7th harmonics and that the power factor is low due to inductive motor loads. This is expected since the pump motors are connected directly to the line.

Table 1: Fluke Meter Screen Shots of measurements at Site A

Real & Reactive Power	Harmonics
	

Site Survey Conclusion:

The SMWD site enabled direct access to 480Vac three-phase loads for power, whereas the UCI and Pacific Transformer site used 208Vac three-phase. Given that most industrial and water applications will be at 480Vac, and the SMWD site offered the most dynamic loads, the OCC team focused on the 50Arms at 480Vac APF.

CHAPTER 3: Test Results

As the first step, the OCC-APF was developed and tested in the OCC laboratory to ensure readiness for the field demonstration. The sections below provide a summary of the laboratory and the field test results.

Laboratory Test Results

The OCC team tested the OCC-APF in the OCC laboratory according to the setup shown in Figure 5. High-powered non-linear (Harmonic) and reactive loads were connected to the 480 Vac side of a 208 Vac to 480 Vac step-up transformer. The OCC-APF connected in parallel with the loads provided the correction currents to correct the power factor and cancel the harmonics of the applied loads.

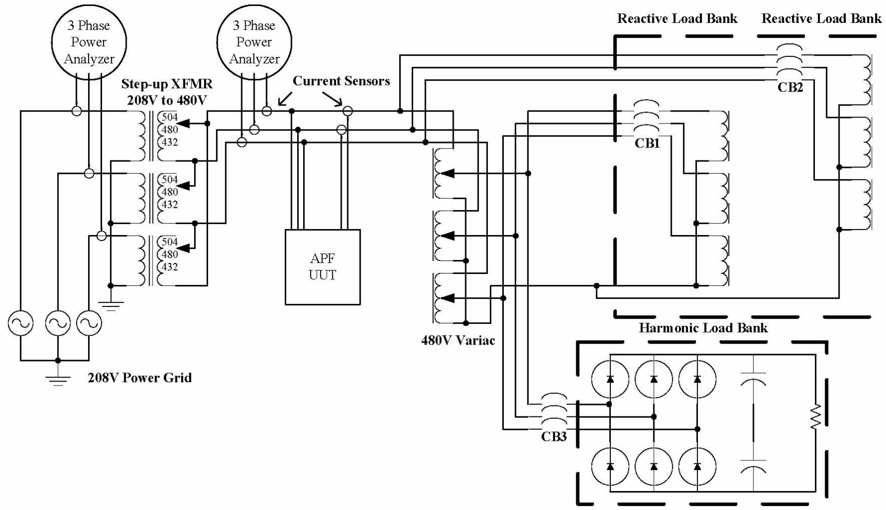


Figure 5: OCC Laboratory OCC-APF Test Setup

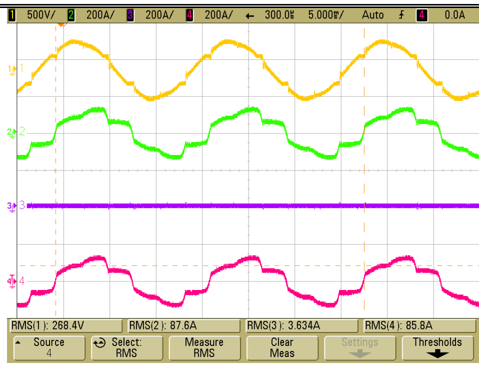
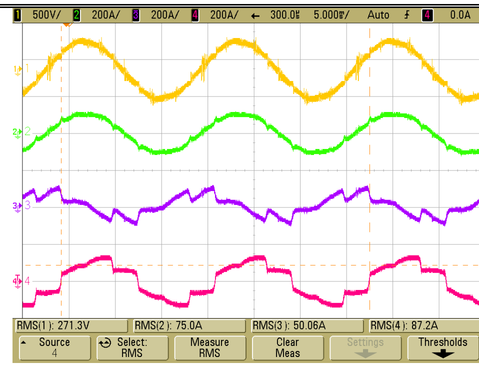
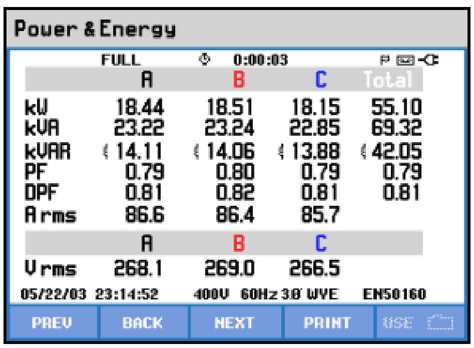
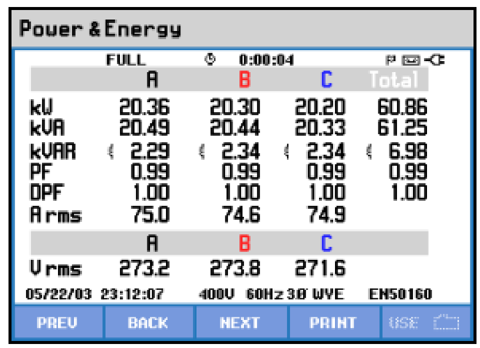
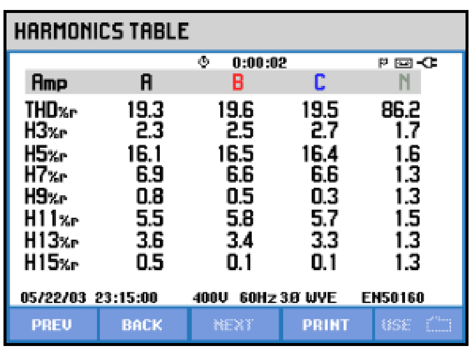
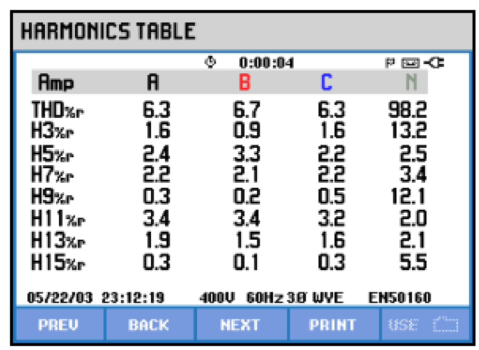
A summary of primary results is shown in Table 2 for non-linear loading of the OCC-APF. The top charts in Table 2 show oscilloscope waveforms captured with the OCC-APF OFF (left) and OCC-APF ON (right). Waveforms displayed (top to bottom) are: Phase A voltage (Va); Phase A grid current (Ia_grid); Phase A APF current (Ia_compensation); and Phase A load current (Ia_load). Clearly, the load current is very non-linear with high harmonic content; the OCC-APF cancels the harmonics and corrects the power factor so that the grid current is sinusoidal and in phase with the Phase A voltage. The power-quality measurements presented below the oscilloscope images show that the Power Factor (PF) is improved from 0.79 to 0.99 while the Total Harmonic Distortion (%THD) is decreased from 19.5 percent to 6.5 percent. The OCC-APF has corrected the power factor and substantially cancelled the harmonic distortion caused by this non-linear load.

The OCC team conducted numerous other tests on the OCC-APF, including sound intensity, thermal profiling, and burn-in testing. All measurements showed the OCC-APF performed within design expectations and achieved desired levels of performance.

Lab Testing Conclusion:

Laboratory testing of the OCC-APF provided excellent data under controlled conditions; a necessary step toward successful field testing. The field testing also revealed the need to include high-inrush testing as part of the future lab-based test suite. See field testing below.

Table 2: Non-Linear Load Laboratory Test Results

OCC-APF OFF	OCC-APF ON
	
	
	

Field Test Results

Following laboratory testing, the OCC team recorded data at the SMWD site. Field testing provided an excellent opportunity to learn and to improve the performance of the OCC-APF. For example, measurements at the field site quickly revealed inrush current during the start up of the facility pumps was greater than 600 Amps peak and caused the OCC-APF to attempt to correct the high current and go beyond its current rating forcing an over current shutdown.

The OCC team then upgraded OCC-APF and reinstalled it at the SMWD site to conduct a series of measurements to verify ride-through capability during high-inrush periods. Measurements presented in Figure 6 show the extremely dynamic load transient. When the pump starts up, the load current jumps within one line cycle (20 msec) to 600 Amps peak (blue waveform), the high current drops down to the steady-state current of 50 Amps peak after 18 line cycles (300 msec).

Previous to the update, the high inrush demanded a very high correction from the APF and the OCC-APF in its attempt to provide it, would shut down due to the high current. With the update, the OCC-APF limits its output current to 100 Amps peak so that it rides through the event without shutting down (red waveform). The result is that the power factor of the line current (green waveform) is not fully corrected during the large transient, but is fully corrected as the peak current decreases after 300 msec.

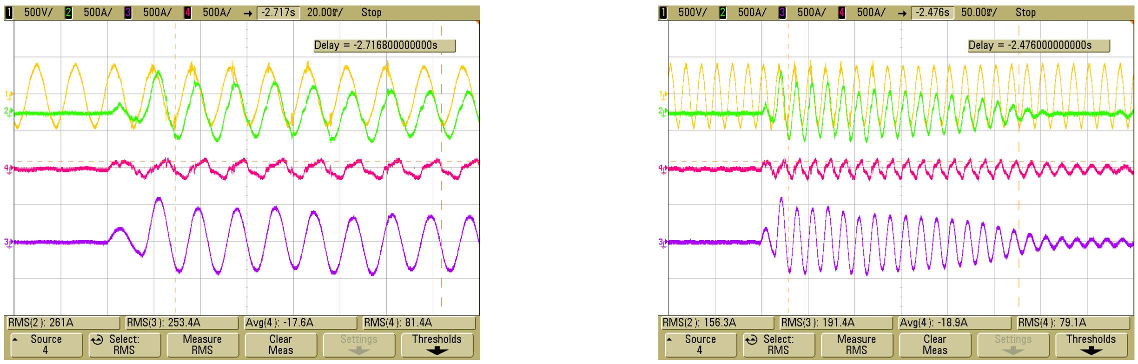


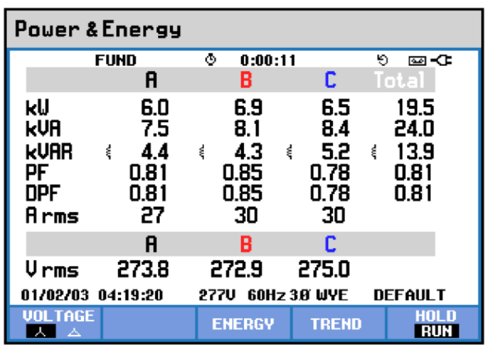
Figure 6: Pump Turn-ON transient zoomed-in (left) and zoomed-out (right)

{Va (yellow); Ia_line (green); Ia_APF (red); Ia_load (blue)}

Table 3: "Small Pump" + "Big Pump" Power Quality Measurements

OCC-APF OFF	OCC-APF ON

OCC-APF OFF



Power & Energy

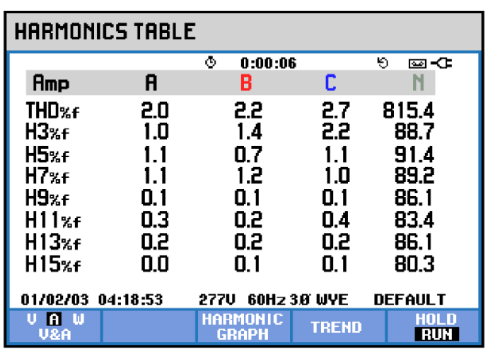
FUND 0:00:11

	A	B	C	Total
kW	6.0	6.9	6.5	19.5
kVA	7.5	8.1	8.4	24.0
kVAR	4.4	4.3	5.2	13.9
PF	0.81	0.85	0.78	0.81
DPF	0.81	0.85	0.78	0.81
A rms	27	30	30	

	A	B	C
V rms	273.8	272.9	275.0

01/02/03 04:19:20 277V 60Hz 3Ø WYE DEFAULT

VOLTAGE ENERGY TREND HOLD RUN



HARMONICS TABLE

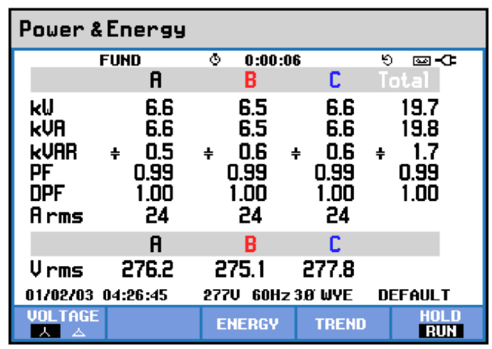
0:00:06

Amp	A	B	C	N
THD%f	2.0	2.2	2.7	815.4
H3%f	1.0	1.4	2.2	88.7
H5%f	1.1	0.7	1.1	91.4
H7%f	1.1	1.2	1.0	89.2
H9%f	0.1	0.1	0.1	86.1
H11%f	0.3	0.2	0.4	83.4
H13%f	0.2	0.2	0.2	86.1
H15%f	0.0	0.1	0.1	80.3

01/02/03 04:18:53 277V 60Hz 3Ø WYE DEFAULT

V A W V&A HARMONIC GRAPH TREND HOLD RUN

OCC-APF ON



Power & Energy

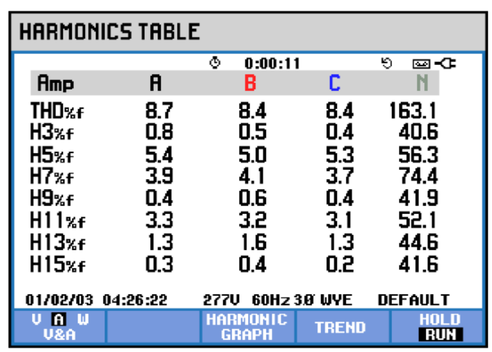
FUND 0:00:06

	A	B	C	Total
kW	6.6	6.5	6.6	19.7
kVA	6.6	6.5	6.6	19.8
kVAR	0.5	0.6	0.6	1.7
PF	0.99	0.99	0.99	0.99
DPF	1.00	1.00	1.00	1.00
A rms	24	24	24	

	A	B	C
V rms	276.2	275.1	277.8

01/02/03 04:26:45 277V 60Hz 3Ø WYE DEFAULT

VOLTAGE ENERGY TREND HOLD RUN



HARMONICS TABLE

0:00:11

Amp	A	B	C	N
THD%f	8.7	8.4	8.4	163.1
H3%f	0.8	0.5	0.4	40.6
H5%f	5.4	5.0	5.3	56.3
H7%f	3.9	4.1	3.7	74.4
H9%f	0.4	0.6	0.4	41.9
H11%f	3.3	3.2	3.1	52.1
H13%f	1.3	1.6	1.3	44.6
H15%f	0.3	0.4	0.2	41.6

01/02/03 04:26:22 277V 60Hz 3Ø WYE DEFAULT

V A W V&A HARMONIC GRAPH TREND HOLD RUN

Following the in-rush testing, the OCC team measured the power quality with both the small pump and the big pump operating (Table 3). The power factor is substantially improved by the OCC-APF from 0.78 to 0.99 when the OCC-APF is ON.

During the 96-day field demonstration period substantial data were recorded using a Fluke Power Quality Analyzer. For the purpose of this report, sample data are shown for the first few days, since this highlights a more dynamic data set. From top to bottom in each figure are plotted: the Corrected Power Factor, the Load Power Factor (before correction), the Load Apparent Power S (kVA), and the Corrected Apparent Power S (kVA). The x-axis shows the time in days. It is worth noting that large transients in the Load result in minor changes in the corrected power factor. Figure 7 shows that the OCC-APF corrects the power factor to approximately 1.0 and reduces the apparent power by approximately 21 percent.

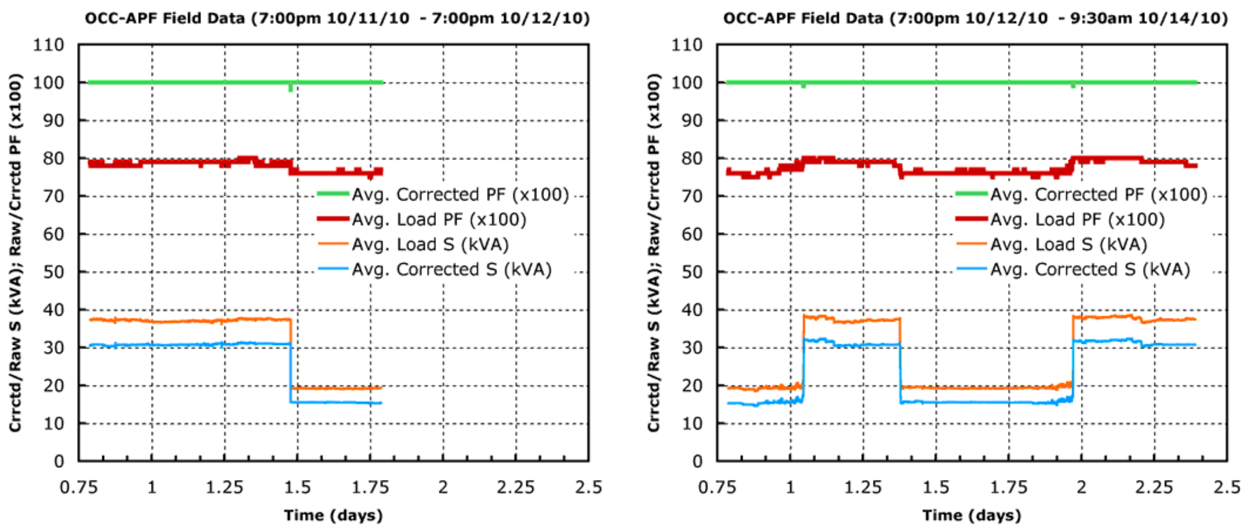


Figure 7: Field Data 10/11~10/12/10 (30 sec interval) **and 10/12~10/14/10** (1 min interval)

Field Testing Conclusion:

Field testing has proved invaluable to the improvement of the OCC-APF product and to the attraction of customers whose confidence was increased by the field testing results.

CHAPTER 4:
Benefits and Drawbacks to OCC-APF Deployment

Benefits: The primary benefit of deploying the OCC-APF is the substantial improvement in power factor that reduces the apparent power through the facility transformer and the entire distribution network upstream of the OCC-APF location. The extremely fast response of the OCC-APF means that in real time, the apparent load is reduced. Therefore, additional loads can be applied to the same infrastructure without infrastructure upgrades. For example, assume a facility has a 1.0 MVA transformer with 900 kVA of load at a 0.8 power factor. Using several OCC-APFs to correct the power factor to 1.0 would result in a reduction of the kVA load to ~720 kVA; therefore, increasing the operating margin of the 1.0 MVA transformer and enabling an increase in facility load without replacing the transformer and switchgear. In regions where power (or peak demand) is charged based on kVAh (kVA peak), the OCC-APF's ability to dynamically correct the power factor in real time could deliver substantial monetary benefit.

A secondary benefit of deploying the OCC-APF is the reduction in harmonic content from high harmonic loads. This can be helpful to reduce neutral line currents in some cases and potential audible noise in other cases. Although prior publications state that current harmonics have a substantial impact on the efficiency of facility transformers, the calculations presented below and the data collected in the laboratory-based experiments at OCC, Inc. tend to indicate that the improved efficiency is nominal at best. It appears that the most significant advantage of the OCC-APF is the dynamic correction of the power factor to increase the grid operating margin. This can have a substantial positive affect on a single facility and can have a dramatic aggregated benefit to the larger-scale distribution network as a whole.

Drawbacks: The primary drawback of deploying an OCC-APF is the added cost necessary to purchase and install the OCC-APF that has both "hard" measurable benefits and "soft" benefits that are typically more difficult to value. In some cases, the soft and hard benefits can be distributed across a facility tenant (looking at electricity bill), facility owner (looking at constrained capacity and need for upgrades), and the utility (looking at constrained capacity through their MV distribution lines and substations). Although, the OCC-APF can release operating margin of the transformer and distribution network, this is a "soft" benefit unless the facility growth is constrained by the lack of free capacity. If a constrained situation exists, then a calculation could be done to compare the capital cost of facility and power distribution upgrades (substation expansion; transformer upgrade; switch-gear upgrades, etc.) with the capital cost of deploying OCC-APFs.

Calculations of Energy Savings & Return on Investment

Energy Savings at Field Site: It was not possible to measure the grid side power input to the field site facility transformer. Therefore, the OCC team completed a calculation (Table 4) to estimate the magnitude of the potential energy savings from improved power factor.

Table 4: Calculation of transformer loss and efficiency at the SMWD field site

Test Condition	Average Loss	Average Efficiency

OCC-APF OFF	69.1 W	99.65%
OCC-APF ON	47.1 W	99.76%

The calculation ignores the Transformer No-Load loss, since it is the same for both APF ON and OFF while providing an estimate of the loss due to differences in the power factor.

According to the data given on the transformer's name plate:

Z=2.7%, which means Z=0.027 (per unit);

$Z_{\text{per unit}} = \frac{Z_{actual}}{Z_{base}}$, where $Z_{base} = \frac{V^2}{S_{base}} = \frac{12000^2}{75000} = 1920$ Ohm

So $Z_{actual} = 1920 \times 0.027 = 51.84$ Ohm

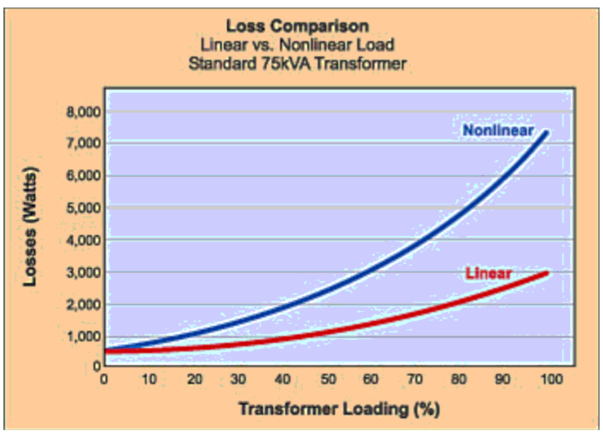
If operating at 75kVA: $I = \frac{S}{\sqrt{3} \cdot V} = \frac{75000}{12000\sqrt{3}} = 3.61A$

$Loss = I^2 \cdot Z_{actual} = 3.61^2 \cdot 51.84 = 675.6W$

When APF is OFF, S = 24 kVA, so the Loss_no comp = 69.1 W

When APF is ON, S = 19.8 kVA, so the Loss_comp = 47.1 W

Based on the calculated result, the OCC team conducted lab-based measurements across a transformer to determine actual losses, since pre-existing literature suggests a greater loss.



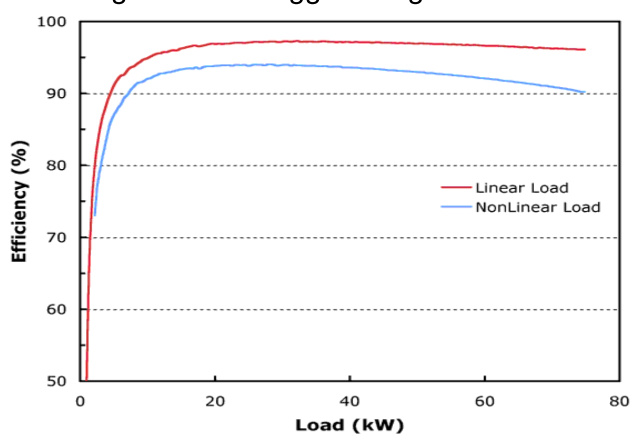


Figure 8: Loss Plot (left) from [1] and calculated Efficiency (right) based on Loss Plot

Figure 8(left) shows a plot of calculated losses for a typical 75 kVA transformer with Linear and Non-linear loading **(Ling 2003)**. The plot is taken from [1] and assumes that the non-linear load consists of single-phase high percent THD current ~ 100 percent; the losses are calculated (not measured) based on standard transformer parameters. Looking at this plot definitely suggests a significant reduction in loss can be achieved by reducing the percent THD. Figure 8(right) is a presentation of the same data as Efficiency rather than Loss; it is worth noting that the calculated transformer efficiency is substantially lower for the Non-Linear load, with high percent THD, compared to the Linear load. Based on these prior data, that indicate a substantial increase in loss (~2x (200 percent) increase in loss) we were led to believe that a significant effect of percent THD could easily be measured in the laboratory. A recent publication **(Moses 2011)** indicates that the efficiency impact of high percent THD loads is much smaller, approximately 0.3 percent increase in loss.

Measured Transformer Efficiency: To determine the potential efficiency benefit of reduced percent THD enabled with Active Power Filtering, the OCC team applied a variety of loads to the 480 Vac side of a 75 kVA low voltage transformer (208 Vac to 480 Vac) while measuring the transformer input and output power with a high-resolution digital power meter (Yokagawa WT1600). The measured efficiency is summarized in Figure 9 (left) for the following loads: "R"=PF~1.0; "NL"=non-linear diode-rectifier load; "NL w C" = non-linear diode-rectifier with capacitor on DC side to increase percent THD; "NL + L" = non-linear plus inductive load; and "L" = pure inductive load. It is worth noting that with the exception of the "L" load, the measured transformer efficiency is independent of the load type over the measured range. Therefore, based on these measurements, the percent THD impact on transformer efficiency is small (<1 percent) and these measurements and somewhat aligned with the ~0.6 percent **(Moses 2011)** rather than the large 200 percent difference reported in [1].

The pure inductive load "L" results in low transformer efficiency, which matches the roll-off in the efficiency curve for the transformer, since the real power draw through the transformer is small. When serving an inductive load, the transformer efficiency reaches a maximum 89 percent, and then decreases as the kVA of the inductive load approaches the kVA limit of the transformer at 50, 60, and 78 kVA.

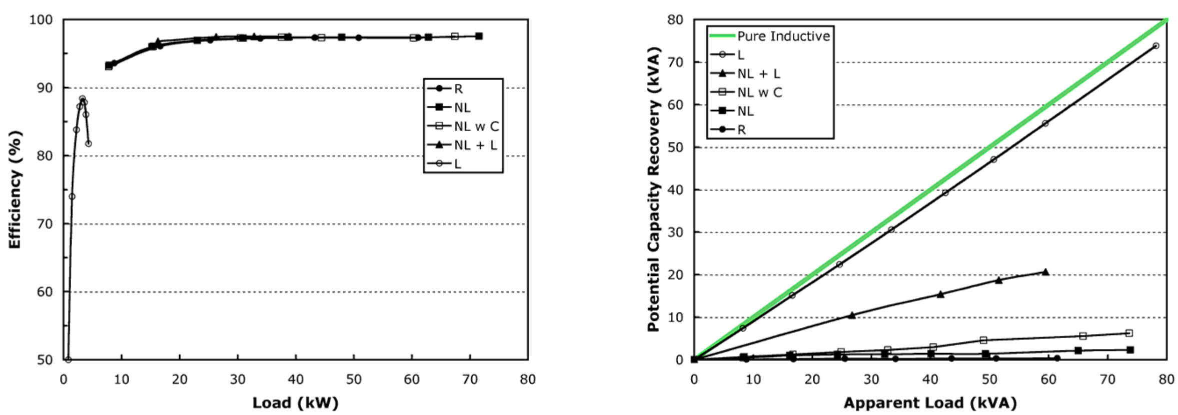


Figure 9: Measured Eff. (left) for various load types and Potential Capacity Recovery (right)

Measured Capacity Recovery: Another significant advantage to reduction of harmonics and correction of power factor is that transformer capacity can be freed up to serve additional load growth without a transformer upgrade. The freed-up capacity also benefits switchgear, protective breakers, and cabling to enable cost-effective load growth. Figure 9(right) shows the potential capacity recovery through correction of power factor and cancellation of harmonics of the same set of loads explored in the above section. Note, that the "NL" and "NL w C" loads have potential for modest capacity recovery of 4 to 8 kVA (5 to 11 percent) and that loads with less desirable power factor, such as the "NL + L" and "L" loads, have potential for 20 to 70 kVA (27 to 90 percent). This capacity recovery can provide a significant value proposition in cases where a facility or distribution network suffers from constrained capacity.

Return on Investment: ROI, to the end user, based on calculations and measurements of energy savings alone result in very modest return that is unlikely, by itself, to justify purchase of the OCC-APF. Instead, it is necessary to look at the other aspects that could result in substantial financial return (e.g. in reduced power factor penalties, kVA peak charges, or kVAh charges) or savings from delayed or eliminated distribution-system upgrades.

kVA Charges: In some utility districts and in some countries, the end user is assessed a substantial charge for kVA peak charges. For example, Connecticut Light & Power (CLP) charges its customers for peak demand in kVA; an incentive to the customer to improve power factor. Customers with peak demand between 350 and 1000 kW are charged $13.27 per kVA peak. Consider a customer with 400 kW peak draw at 0.8 power factor; this would yield 500 kVA peak draw. Improving the power factor to 1.0 would require 300 kVA of OCC-APF (8 units of the 41kVA OCC-APF). The saving would be 100kVA x $13.27/month = $1,327/month ($64,000 in 4 years). At present, the price of an OCC-APF is $12,500 in quantity 10, but with volume the price should fall to enable a target ROI of approximately 4 years.

Capacity Recovery: In some facilities and in some distribution networks, delivery capacity is constrained; e.g. operating near kVA limits of facility transformers, switchgear, distribution cables, substations, etc. In these cases, installation of OCC-APF at the facilities to dynamically improve power factor can release capacity throughout the network to enable the distribution system to support load growth while delaying or eliminating capacity upgrades. Unlike switched capacitor banks, the OCC-APF can provide both leading and lagging power-factor compensation and can adjust across a fine scale, without steps, to deliver precise, real-time correction. The ROI for the capacity recovery requires involvement of utilities and detailed calculations of deferred/eliminated network upgrades.

CHAPTER 5: Conclusions

The OCC-APF performs dynamic power factor correction and harmonic cancellation, rapidly, precisely, and efficiently. The OCC-APF is ~5x to ~10x smaller and lighter than typical APF product offerings in the market and therefore requires substantially less raw material to manufacture. The OCC-APF can be connected in parallel to achieve correction of power factor and harmonics in high-power applications. For example, 12 units installed in a full-height rack deliver ~480kVA of correction capacity, enough for a facility with a 1.5 to 2.0 MVA service.

The OCC-APF value proposition varies with utility rate schedules, type of facility loads, and capacity constraints of the facility/utility distribution network. Several global and domestic markets exist where a suitable ROI is justified by peak kVA or kVAh charges defined on end-user rate-schedules. For example, Connecticut Light & Power customers with peak demand between 350 and 1000 kW are charged $13.27 per peak kVA. A customer with 400 kW peak draw at 0.8 power factor would have ~500 kVA peak draw and an annual charge of $79,620. Dynamically correcting the power factor to 1.0 using multiple OCC-APFs could save $15,924 each year and deliver an ROI of approximately 4 years.

Utility markets may also exist, whereby efficiency improvement and capacity release enable more efficient and improved utilization of existing transmission and distribution assets. Assessment of these advantages requires detailed calculations and the involvement of utilities to determine the value of customer load growth while deferring or eliminating asset investment in network upgrades. Provided a suitable case can be made at the utility level, then utility investment in OCC-APF deployment at multiple node points on the distribution network may be preferable over other network upgrade approaches.

Recommendation for Future Demonstration

This program has promoted the development of a robust OCC-APF product that is ready for commercial sale with demonstrated benefit to individual facilities. The OCC-APF can also deliver benefit to large-scale distribution networks; to assess these it is necessary to deploy many OCC-APFs under controlled monitoring and assessment. The OCC team recommends a demonstration on a heavily loaded distribution branch with utility involvement or in a large-scale capacity-constrained facility (or institution) so that aggregated benefits can be evaluated. This large-scale demonstration would enable insight into the value of relieving congestion caused by reactive currents so that network upgrades could be deferred or become unnecessary.

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GLOSSARY/ACRONYMS:

APF	Active Power Filter
DOD	Department of Defense
DOE	Department of Energy
OCC	One-Cycle Control
PT	Pacific Transformer
ROI	Return on Investment
SMWD	Santa Margarita Water District
UCI	University of California Irvine
PEL	Power Electronics Lab

APPENDIX A:
OCC-APF Brochure