AT LOAD POWER FACTOR CORRECTION

FINAL REPORT
AUGUST 2010

Energy. Innovation. Solutions.

Energy. Innovation. Solutions.

The New York State Energy Research and Development Authority (NYSERDA) is a public benefit corporation created in 1975 by the New York State Legislature.

NYSERDA derives its revenues from an annual assessment levied against sales by New York's electric and gas utilities, from public benefit charges paid by New York rate payers, from voluntary annual contributions by the New York Power Authority and the Long Island Power Authority, and from limited corporate funds.

NYSERDA works with businesses, schools, and municipalities to identify existing technologies and equipment to reduce their energy costs. Its responsibilities include:

- Conducting a multifaceted energy and environmental research and development program to meet New York State's diverse economic needs.
- The New York Energy $martSM program provides energy efficiency services, including those directed at the low-income sector, research and development, and environmental protection activities.
- Making energy more affordable for residential and low-income households.
- Helping industries, schools, hospitals, municipalities, not-for-profits, and the residential sector, implement energy-efficiency measures. NYSERDA research projects help the State's businesses and municipalities with their energy and environmental problems.
- Providing objective, credible, and useful energy analysis and planning to guide decisions made by major energy stakeholders in the private and public sectors.
- Since 1990, NYSERDA has developed and brought into use successful innovative, energy-efficient, and environmentally beneficial products, processes, and services.
- Managing the Western New York Nuclear Service Center at West Valley, including: overseeing the State's interests and share of costs at the West Valley Demonstration Project, a federal/State radioactive waste clean-up effort, and managing wastes and maintaining facilities at the shut-down State-Licensed Disposal Area.
- Coordinating the State's activities on energy emergencies and nuclear regulatory matters, and monitoring low-level radioactive waste generation and management in the State.
- Financing energy-related projects, reducing costs for ratepayers.

For more information, contact the Communications unit, NYSERDA, 17 Columbia Circle, Albany, New York 12203-6399; toll-free 1-866-NYSERDA, locally (518) 862-1090, ext. 3250; or on the web at www.nyserda.org

AT LOAD POWER FACTOR CORRECTION

Final Report

Prepared for the

NEW YORK STATE ENERGY
RESEARCH AND
DEVELOPMENT AUTHORITY

Energy. Innovation. Solutions.

Albany, NY
www.nyserda.org

Michael P. Razanousky
Project Manager

Prepared by:
POWER FACTOR CORRECTION, LLC

Richard Ellenbogen, MEE
Project Manager

NYSERDA
Report 10-36

NYSERDA 11059

August 2010

CONTENTS

Section Topic **Page**

1 Project Objectives and Background Information 4
  1.0 Project Introduction, Objectives and Overview 4
  1.1 Background 5

2 Industrial and Commercial Application 13
  2.0 Background and Conclusions – Industrial 13
  2.1 Implementation 14
  2.2 Results and Analysis 16
  2.2.1 500 KW Manufacturing Facility 16
  2.2.2 150 KW Peak Load Supermarket 20
  2.3 Cost/Benefit Analysis – Industrial/Commercial 23
  2.3.1 500 KW Manufacturing Facility 23
  2.3.2 150 KW Peak Load Supermarket 23
  2.3.3 Additional Observation 24
  2.4 Conclusions – Industrial/Commercial 24

3 Refrigerated Vending Machines 26
  3.0 Background and Conclusions – Refrigerated Vending Machines 26
  3.1 Implementation 28
  3.2 Important Facts about Vending Machines that will affect an Efficiency Program 30
  3.3 Data Analysis 32
  3.4 Cost/Benefit Analysis - Refrigerated Vending Machines 37
  3.5 Conclusions 38

4 Multi Family Residential 40
  4.0 Background and Conclusions – Multi Family Residential 40
  4.1 Implementation 42
  4.2 Observations about customer behavior and the service area that will affect an Efficiency Program 46
  4.3 Data Analysis 47
  4.4 Cost/Benefit Analysis - Multi Family Residential 51
  4.5 Conclusions – Multi Family Residential 53

5 Single Family Residential 55
  5.0 Background Information and Implementation 55
  5.1 Results 58
  5.2 Other Issues Encountered in the Single Family Residential Residential Environment that affect Energy Efficiency 61
  5.2.1 Larger Single Family Homes 61
  5.2.2 Load Balancing Between Phases 62
  5.2.3 Charlatans Selling Power Factor Correction 64
  5.3 Conclusions 66

Section Topic **Page**

6 Harmonic Analysis 68

7 "At Load" Reactive Power Correction versus "Service Entrance" Power Factor Correction 75

8 Economic Analysis Comparing "At Load" Correction Costs For Various Sized Services 76

9 Summary of Conclusions – Overall Project 80

10 Acknowledgements 82

1 – PROJECT OBJECTIVES AND BACKGROUND INFORMATION

1.0 Project Introduction, Objectives, and Overview

Power Factor is the ratio of the power needed to do the work within customer premises to the power delivered by the utility. A power factor of 1.0 is ideal. Equipment located in customer premises emits reactive power that lowers the power factor. There are devices that can be attached to the loads to raise the power factor and reduce the amount of energy lost as heat on the wires in buildings and on the electrical distribution system.

This paper presents the background information, method, and results from an eighteen month long pilot project designed to determine the economic feasibility of "At Load" power factor correction in various scenarios as a method for improving efficiency and reducing losses on the electric utility system. "At Load" power factor correction will be analyzed in multi-family dwellings (apartments), single family residences, commercial buildings and industrial buildings. As power factor correction is not a new concept, the project had four objectives. For all phases of the project, our first objective was to measure the power factor in the different environments. This involved creating data bases to simplify handling of the data being collected. Second, we wanted to gain a better understanding of the reactive loads in the different environments. That understanding includes the age of the appliances or equipment discharging the reactive power and the types of installations involved. Our third objective was to correct the power factor in the most cost effective manner possible. Our final objective was to measure the effect of our installation and determine the cost versus benefit of the installations. Benefit is measured in Kilowatt Hours (KWH) saved.

While the results presented for all of the test environments will be similar, the magnitudes of improvement and the related costs vary from environment to environment. Also, the volume of data being collected and the timeframe of the data collection at the different sites mandated that we divide the project into four phases. This is a summation of the results from all phases of the project. There are individual papers for the Industrial/Commercial analysis, the Vending Machine analysis, and the Multi Family Dwelling analysis phases of the project. The Single Family Residential Data is documented in Part 5.

Many of the references in the paper are to the Transmission and Distribution system in New York, as the work was done there. Nevertheless, the results are valid for nearly all AC distribution systems.

1.1 Background

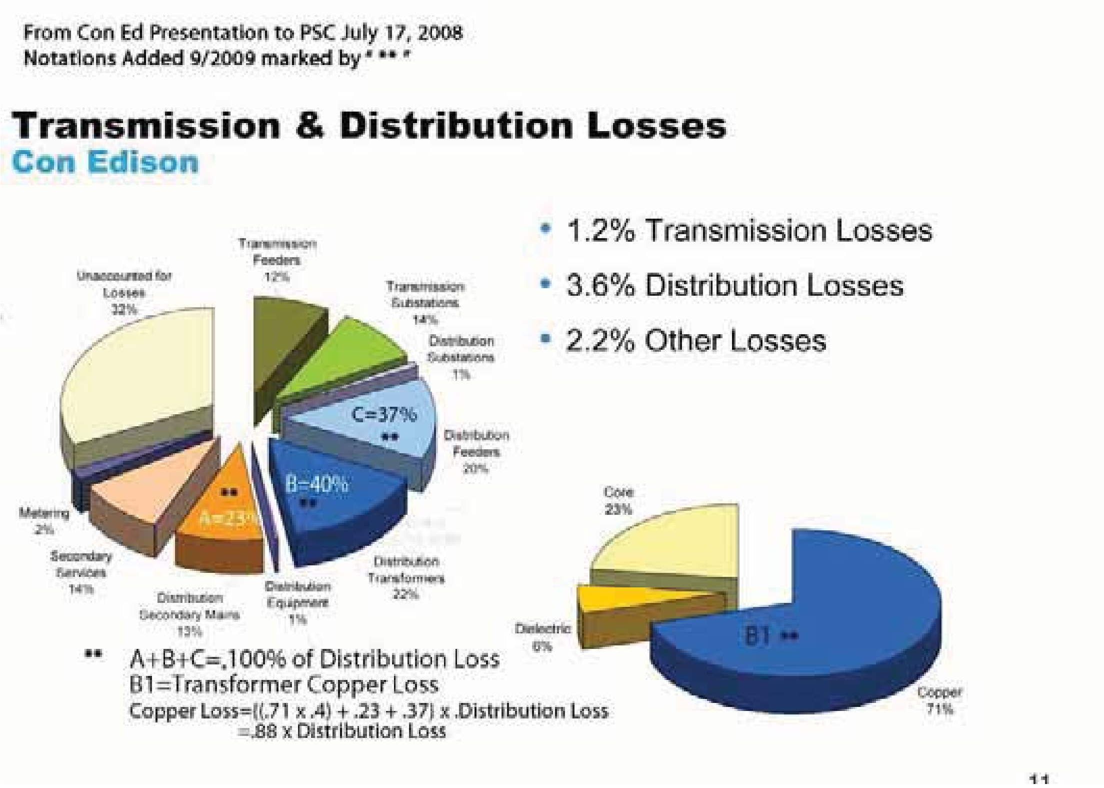
Power Factor is the ratio of the power needed to do the work within customer premises to the power delivered by the utility. The power needed by customer premise equipment to operate is measured in Kilowatts (KW). The amount of power delivered by the utility is measured in Kilovolt Amperes (KVA). KW divided by KVA is the power factor. A power factor of 1.0 is ideal. Appliances and machinery within customer premises discharge reactive power, measured in Kilovolt Amperes Reactive (KVAR). More KVAR present on the utility system results in a lower power factor, and higher currents (I) present on the wires. Because thermal losses on the wires are proportional to the square of the current, a 12 % increase in current will result in a 25% increase in thermal losses related to the increased current. (1.12 x 1.12=1.25). Similarly, a 10% current reduction will result in a 19% drop in thermal losses and provide the corresponding energy savings (0.9 x 0.9 = 0.81). Additional information explaining power factor and the associated energy losses can be found on-line at www.wikipedia.org or on our web-site, www.powerfactorcorrectionllc.com .

Historically, utilities have implemented power factor correction at their substations by installing banks of capacitors. The substations are where the utilities reduce the voltage (usually greater than 110,000 volts) from the transmission wires to lower voltages (4,100 volts or 13,000 volts) for distribution throughout the service area. The voltages are further reduced to the range of 208 volts to 480 volts at the transformers on the utility poles or in underground vaults located near the customer premises. The problem with implementing power factor correction at the substations is that the reactive power present on the distribution system, not serviced by those capacitors, is inducing thermal losses. Furthermore, the distribution system, with its lower voltages and higher currents, already accounts for the majority of the losses on the system. In addition, more thermal losses occur on the customer side of electric meter, within the customer premises. On the Transmission and Distribution System, 50% of the energy lost and almost 75% of the "Accounted For" energy losses occur on the lower voltage Distribution Portion of the system (See Figure 1). Those figures do not include losses from reactive load that occur after the customer meters. While the utility does not bill for reactive power in most cases, excess thermal losses after the meter caused by reactive load would be measured in watts and would be billed. The losses, while relatively small for any single location, when aggregated throughout New York State, are very significant.

The inadequate capacity on the distribution system is becoming an issue of great concern with the pending introduction of inexpensive electric vehicles in late 2010 and the first quarter of 2011. On March 30, 2010, Nissan announced that its Leaf Electric vehicle would go on sale in April, with delivery starting in the fourth quarter of 2010 at a net price of less than $26,000. An article in IEEE Spectrum from January, 2010 indicates that only two or three vehicle chargers on one local distribution transformer could cause a failure [1]. Effectively increasing the capacity of the distribution system by 7% to 10%, by removing the reactive load, would greatly help to alleviate part of that problem.

Traditional thinking, as evidenced in articles written as recently as May 2007 [2], assumes that the losses only occur in the wires. Calculations have been done on the losses based on the ohms per foot of a length of copper wire. Still, in many buildings, especially older buildings, the majority of the losses occur at the junctions. These include screw connections on switches, receptacles, and breaker panels, the metal-metal interface of a switch or of a plug in a receptacle, circuit breakers, and wires in junction boxes connected by wire nuts. As these copper and copper alloy connections age, they oxidize. This oxidation increases resistance and the associated losses.

The result is that any excess current will increase thermal losses within customer premises.



From Con Ed Presentation to PSC July 17, 2008
Notations Added 9/2009 marked by " ** "

Transmission & Distribution Losses
Con Edison

- 1.2% Transmission Losses
- 3.6% Distribution Losses
- 2.2% Other Losses

** A+B+C=,100% of Distribution Loss
B1=Transformer Copper Loss
Copper Loss=((.71 x .4) + .23 + .37) x .Distribution Loss
=.88 x Distribution Loss

Figure 1: Excerpted from Transmission and distribution Losses. Consolidated Edison. Originally presented July 17, 2008 Percentage Notations added September, 2009.

---

[1] "Speed Bumps Ahead for Electric Vehicle Charging", Peter Fairley, IEEE Spectrum, January, 2010

[2] "Is Power Factor Correction Justified for the Home", William Rynone, President, Rynone Engineering, Power Electronics Technology, May 2007 http://www.powerelectronics.com

As many of the buildings in New York are older and have older electrical services, the connections will have more oxidation and higher resistances (R). That will result in higher I^2R (thermal) losses at those connections. Any system that can reduce currents in the aging wires and connections will result in energy savings. As higher operating temperatures in system components cause more rapid aging of those parts, reducing currents and the associated heat will also add longevity to the system and devices attached to it. By reducing the currents at the load, the savings accrue from the load all of the way back to the first substation where power factor correction is traditionally employed. In addition, by increasing the power factor on the distribution system, existing capacitance is freed at the substation to be used to further raise the power factor on the transmission system on hot days when there are increased loads. That would yield additional energy savings on the transmission system.

According to Figure 1, 7 % of the energy that enters the transmission and distribution system is lost before it reaches the customer. The national average is 7.2%. Of that 7.0 %, 3.6% is lost on the distribution system that is not serviced by the utility's capacitors. We are primarily concerned with those losses and the losses after the customer's utility meter. In Figure 1, transformer losses are shown in the pie chart at the lower right. Twenty-nine percent of the losses in the transformer are "no load" losses and are related to eddy currents in the iron core of the transformer and dielectric losses. Those losses are fixed for a given transformer and will not vary with current. The segment marked "B1" represents the copper losses. Those losses occur in the wires of the transformer and will increase with increasing current.

In Figure 1, according to the pie chart on the upper left, on the distribution system 23% of the losses occur in the secondary mains, 37% of the losses occur in the distribution feeders, and 40% of the losses occur in the transformers. Seventy-one percent of that 40% occurs in the transformer copper, resulting in 28.4% of distribution lo occurring in the transformer windings. The result is that 88% of distribution (thermal) losses, amounting to 3.17% of all energy generated, occurs in the wires of the distribution system that is not serviced by power factor correction. That is a yearly average. It is lower than that during the winter, and higher than that during the summer. Figure 2 indicates that the losses during the warmer, summer months are more than double those during the cooler, winter months. Based on those values, the summer losses can be over 4%. On the 13 Gigawatt Con Ed system, that 4% translates to over 520 megawatts on a day with peak load. To put that into perspective, the new NYPA (New York Power Authority) combined cycle gas turbine power plant in Queens, N.Y. generates 500 megawatts at peak output. Depending on the type of fossil fuel generation being considered, power plant efficiencies can be as low as 25% to 30% for the older coal power plants to 55% for the new combined cycle gas fueled generating plants[3].

---

[3] Electric Generation Efficiency, Working Document of the NPC Global Oil & Gas Study, Made Available July 18, 2007, NATIONAL PETROLEUM COUNCIL , POWER GENERATION EFFICIENCY SUBGROUP OF THE DEMAND TASK GROUP OF THE NPC COMMITTEE ON GLOBAL OIL AND GAS

The average efficiency of delivered energy to the customer, after factoring in generating losses and transmission and distribution losses, is approximately 33%. Of every three watts of energy consumed at the generating plant, only one watt reaches the customer's meter. More energy is lost through inefficiencies after the meter, within the customer premises. Any system that can reduce load, including load caused by distribution losses, will save approximately three times that amount of energy at the generating plant. Associated greenhouse gas production and emission of other pollutants will also be reduced proportionally.

Figure 2 shows the average losses in summer versus winter and the seasonal net energy usage. It can be seen that losses during the summer months are 2.2 times higher than during the winter months. The higher summertime electric load results in heating of all components of the transmission and distribution system. In addition, there is less convective cooling of components as a result of the higher ambient air temperatures. More direct sunlight and more hours of daylight result in a far greater solar load. When all of these factors are combined, the result is that the entire system operates at an elevated temperature. As the temperature of

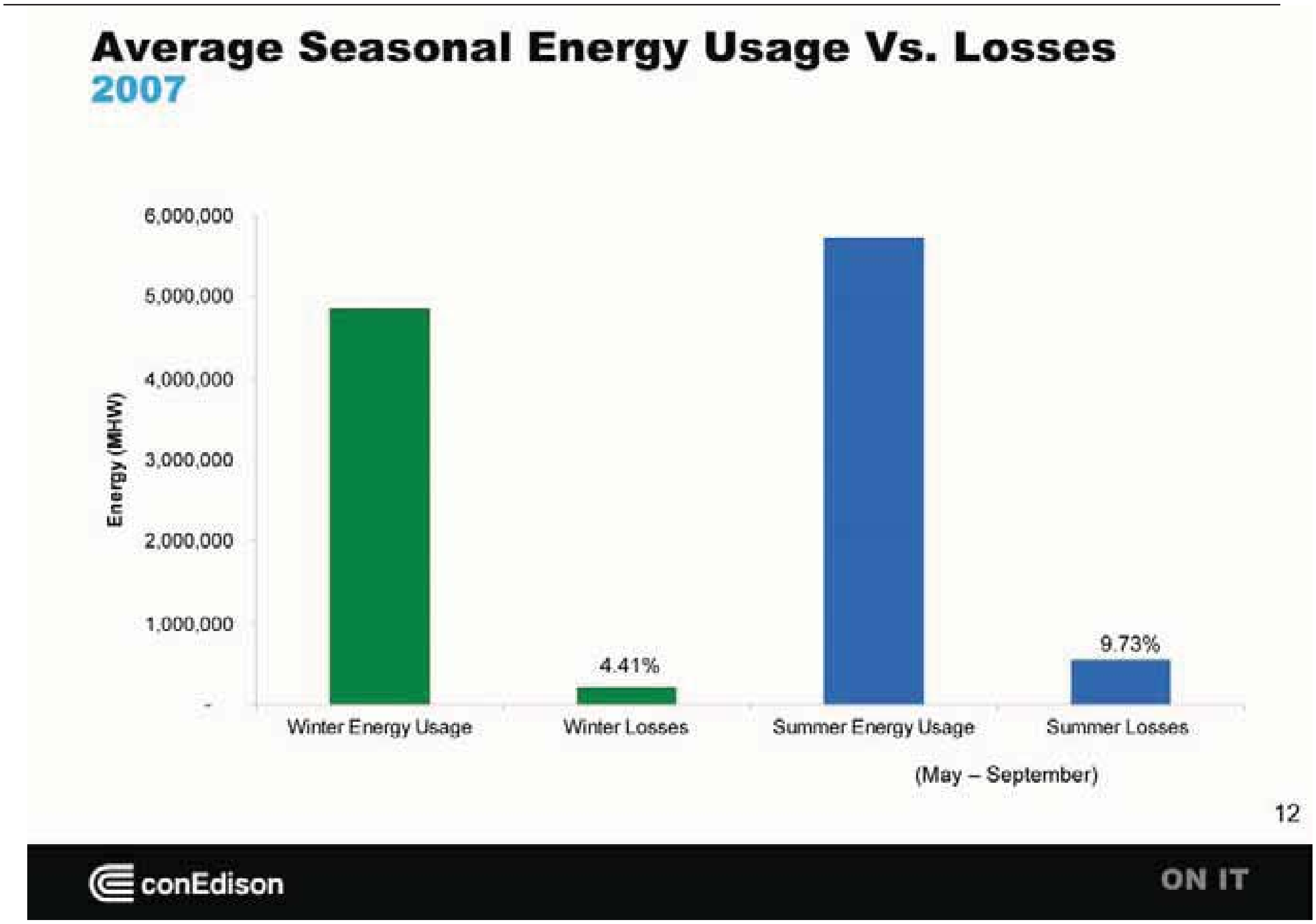


Figure 2: Excerpted from Transmission and distribution Losses. Consolidated Edison. Originally presented July 17, 2008

electrical conductors increases, their resistance increases proportionally. The equation below explains the effect of temperature on the resistance of electrical conductors.[4]

$$R = R_{ref}\,[1 + \alpha(T - T_{ref})]$$

Where: R = Conductor resistance at temperature "T"
R_{ref} = Conductor resistance at reference temperature T_{ref}, usually 20° C, but sometimes 0° C.
α = Temperature coefficient of resistance for the conductor material.
T = Conductor temperature in degrees Celcius.
T_{ref} = Reference temperature that α is specified at for the conductor material.

For copper $\alpha = 0.004041$ per degree-C. The result is that a 10 degree-C (18 deg-F) temperature rise will yield a 4% increase in the resistance of a copper conductor. As thermal losses in wires are proportional to the resistance (R), the line losses increase proportionally. Additionally, as the thermal losses increase, the conductor's temperature rises still further and the resistance continues to increase. This process continues until the conductor temperature reaches equilibrium (heat gain from all sources=heat loss to air or surrounding environment) or in the extreme case, the conductor or transformer will overheat and suffer catastrophic failure.

By reducing currents only 7%, the associated thermal losses will be reduced by 14%. That reduction will be augmented as less thermal loss results in lower conductor temperatures, resulting in a lower conductor resistance. Figure 3 shows the before and after KW usage of a facility that was corrected during 2007. It can be seen that the "before" usage was continuously higher than the "after" usage.

When comparing the two sets of data, we were careful to ensure that the loads were the same. The visible difference is from the reduction of line losses in the facility, resulting from the reduction of reactive load. Even during the lunch hour, which appears as the dip on the graph between 11:50 and 12:30, the KW consumption is reduced. All of the machines would have been idling during that period, except the air compressors. This reduction was achieved in a building that had an electrical service that was only five years old and installed to the latest codes. Oxidation at the wire terminations is minimal, as a result of that. In an older building, the results will be more dramatic.

---

[4] Temperature Coefficient of Resistance: Physics of Conductors, http://www.allaboutcircuits.com/vol_1/chpt_12/6.html

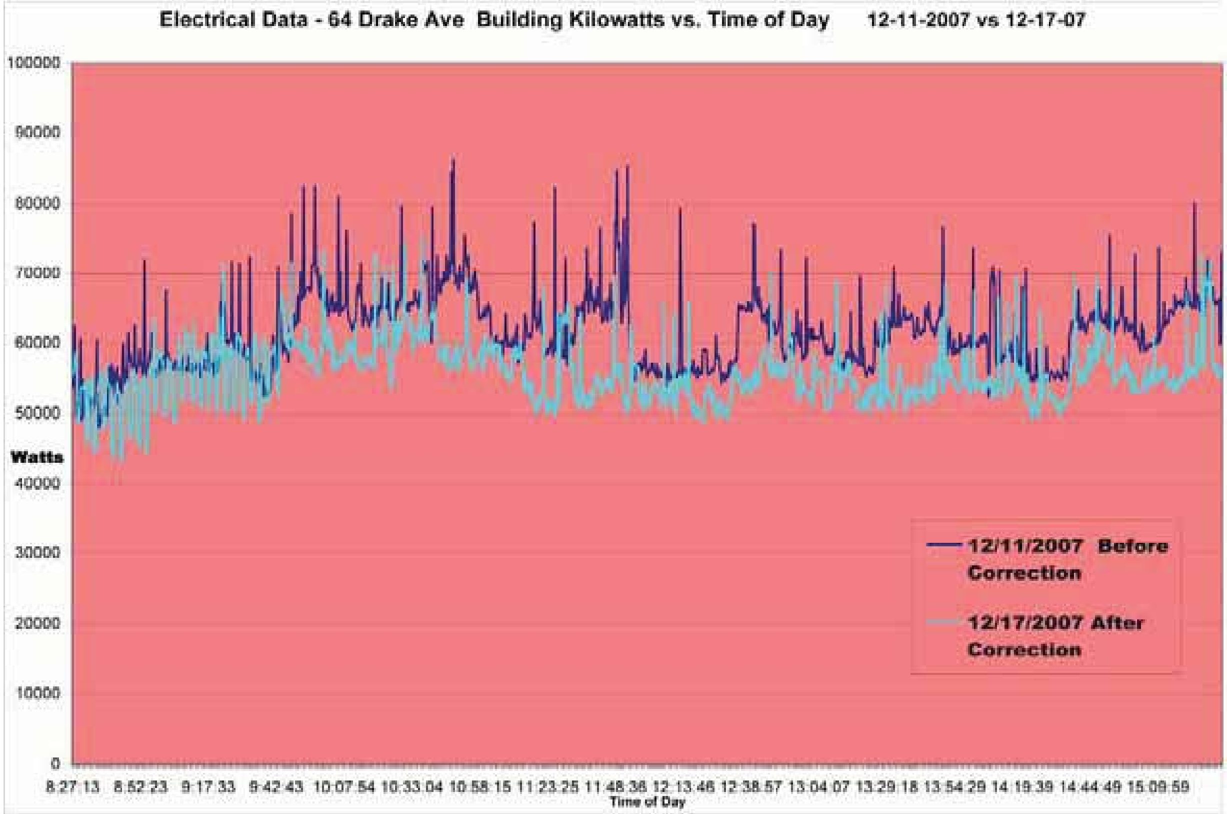


Figure 3 – Customer premise power (KW) usage, before and after reactive power correction. The same equipment was operating on both days, as can be seen from the nearly parallel usage characteristics. The offset is a result of the decrease in consumption caused by raising the power factor from 0.7 to 0.95.

At peak load during the summertime, thermal losses caused by reactive power can consume between 250-MW and 300-MW of generation in the Con Ed service area, including losses within customer premises and on the utility's distribution system. That <u>does not</u> include reactive losses on the transmission system.

The present day cost of that generating capacity is approximately $2000/kilowatt in the New York area, or between $5 billion and $6 billion. There is also a cost to upgrade and maintain substation capacitance to correct the reactive load at that level. Transmission and distribution capability also has to be maintained or upgraded to transfer the additional power to the customer. In addition, substation capacitance does not prevent the associated energy losses on the distribution system. It only reduces the losses on the transmission system. (See Figure 4). As mentioned earlier, those thermal losses, and the associated elevated temperatures, degrade components on the system. The excess load also reduces the amount of usable energy that can be delivered to the customer.

While reducing load will certainly reduce maintenance costs on the distribution system, we did not figure those savings into our economic calculations for two reasons. The primary reason is that there are so many variables involved in the associated costs of maintaining the distribution system, it would be extremely difficult to design a model that would accurately determine reactive power's effect on the maintenance costs. The second reason was that, after calculating the other economic benefits of the process, the additional savings on distribution system maintenance were "icing on the cake".

The primary goal of this project was to determine the amount of loss reduction achievable through adjusting the power factor of various types of building loads and the associated economics of the process.

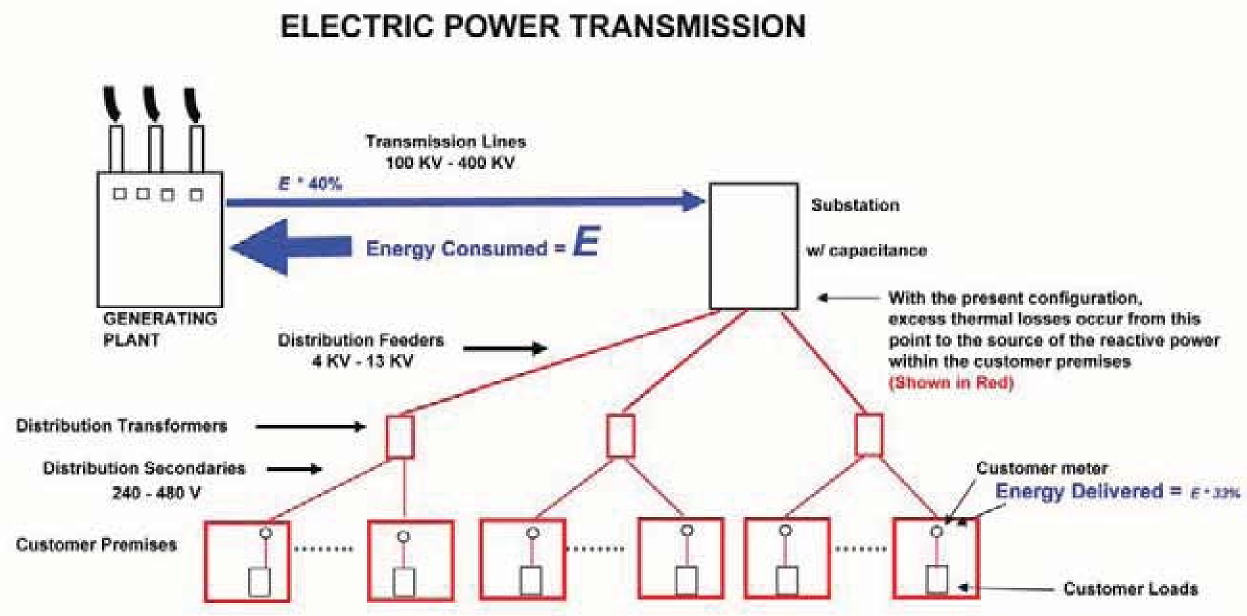


Figure 4 – Block diagram of the electric power transmission system. At present, the utilities correct reactive power at the substations. The distribution system, shown in red, operates with a less than optimal power factor. "At Load" power factor correction will reduce the losses on that entire part of the system.

One possible side effect of performing power factor correction can be increased levels of harmonics. Harmonics are waveforms present on the utility system that have a frequency that is a multiple of the system frequency of 60 hertz (hz). (e.g.: 120 hz-2nd harmonic, 180 hz-3rd harmonic, 240 hz-4th harmonic, etc.). The odd numbered harmonics (180 hz, 300 hz, etc.), cannot be used by equipment on the system. They are absorbed into the components on the system and dissipated as heat. Harmonics can also damage electrical equipment in certain circumstances. For example, harmonics that enter a transformer cause eddy currents in the magnetic core, which are released as heat. In capacitors, harmonics can cause destructive resonances. Sources of harmonics on the utility system include ballasts on some fluorescent lighting and switching power supplies on TV's and computers, among others. One goal of the project was to determine if there would be an increase in harmonics and the associated undesirable effects resulting from them, after installing power factor correction at the various locations. Harmonics are discussed in detail in section 6.0 starting on page 67.

2 – INDUSTRIAL AND COMMERCIAL APPLICATIONS

2.0 Background and Conclusions - Industrial

Accurate data is not available on the number of services in each kilowatt range in the New York metropolitan area, however, Con Ed recently initiated a new tariff that will go into effect over the next three years for services above 500 kilowatts of peak demand. Approximately 7000 meters are affected by this new tariff.

While much of this documentation will reference the New York Metropolitan Area as the work was done here, it is applicable to other areas of the country as well. Conclusions that we have drawn from the work completed to date are the following:

- The power factor is sufficiently low in commercial and industrial buildings that improving it will result in a substantial energy savings throughout the entire utility system, when measured in KWH.
- We can cost effectively improve the power factor for commercial and industrial buildings using the “At Load” technique.
- Standards need to be modified so that new commercial and industrial buildings, and their associated process equipment, are designed with a high power factor as part of the design criteria.
- “At Load” Power Factor Correction in this environment does not greatly increase the amount of harmonics.
- “At Load” Power Factor Correction in this environment will reduce CO_2 emissions by approximately 30 tons annually for each corrected facility of greater than 500-KW, and by approximately 11 tons annually for each corrected facility of greater than 150-KW.
- Power Factor Correction must be load based and must only operate when needed. Excess capacitance connected to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance

would add extra impedance that would have to be energized, applying extra load to the system during a restart.

- In most applications, "At Load" correction has significant advantages over "Service Entrance" correction with respect to energy savings, cost, return on investment, and reduced levels of equipment damaging harmonics.

2.1 Implementation

Implementation of the "At Load" Power Factor Correction for the industrial locations was relatively simple and involved the following steps:

1. **Acquiring Funding**: This was provided through a NYSERDA grant to offset the cost of equipment that would be installed within the customer premises.

2. **Acquiring Test Sites** : Upon confirming that we had project funding, we proceeded to look for building owners that would be willing to participate in the project.

3. **Initial Measurements** : The first step of the process is a walk through of the facility to look at the equipment located on site. Certain types of equipment are likely sources of reactive power. Those include screw compressors, air conditioning equipment, machinery with fly wheels, and large blowers, among others. The second step is to take measurements at the service entrance of the facility over an extended period of several hours during the building's prime operating period to determine the reactive load and power factor of the facility. The third step in the process is to take measurements at the interconnection point of obvious sources of the reactive load to determine each machines load characteristics and how much reactive power they are discharging onto the system. Step four involves calculating the size of the devices that need to be attached to each piece of equipment to correct the problem.

4 **Preparation of an Equipment Order and Acquisition of Correction Devices:** The total size of the facility's KW load, its reactive load, and the facility power factor will determine which locations receive correction. To raise the power factor to 0.97 does not require correcting every piece of equipment in a building. After a certain point, there is a diminishing return to adding correction. The additional cost of the device and installation will not be justified by the return on investment. Smaller loads, in relation to other loads within the facility, will likely not need to be corrected in order to achieve a final power factor of 0.97.

5 **Equipment Installation:** During installation, we attached a data logging meter at the facilities service entrance to record the effect of each device as it was installed. Correction devices were wired to the starting contactors of the equipment so that they would only engage when the associated motor turned on. If possible, it is better to connect the correction devices on the utility side of the thermal overload, but after the contactor. If that is not possible, the overload values of the contactor will have to be adjusted.

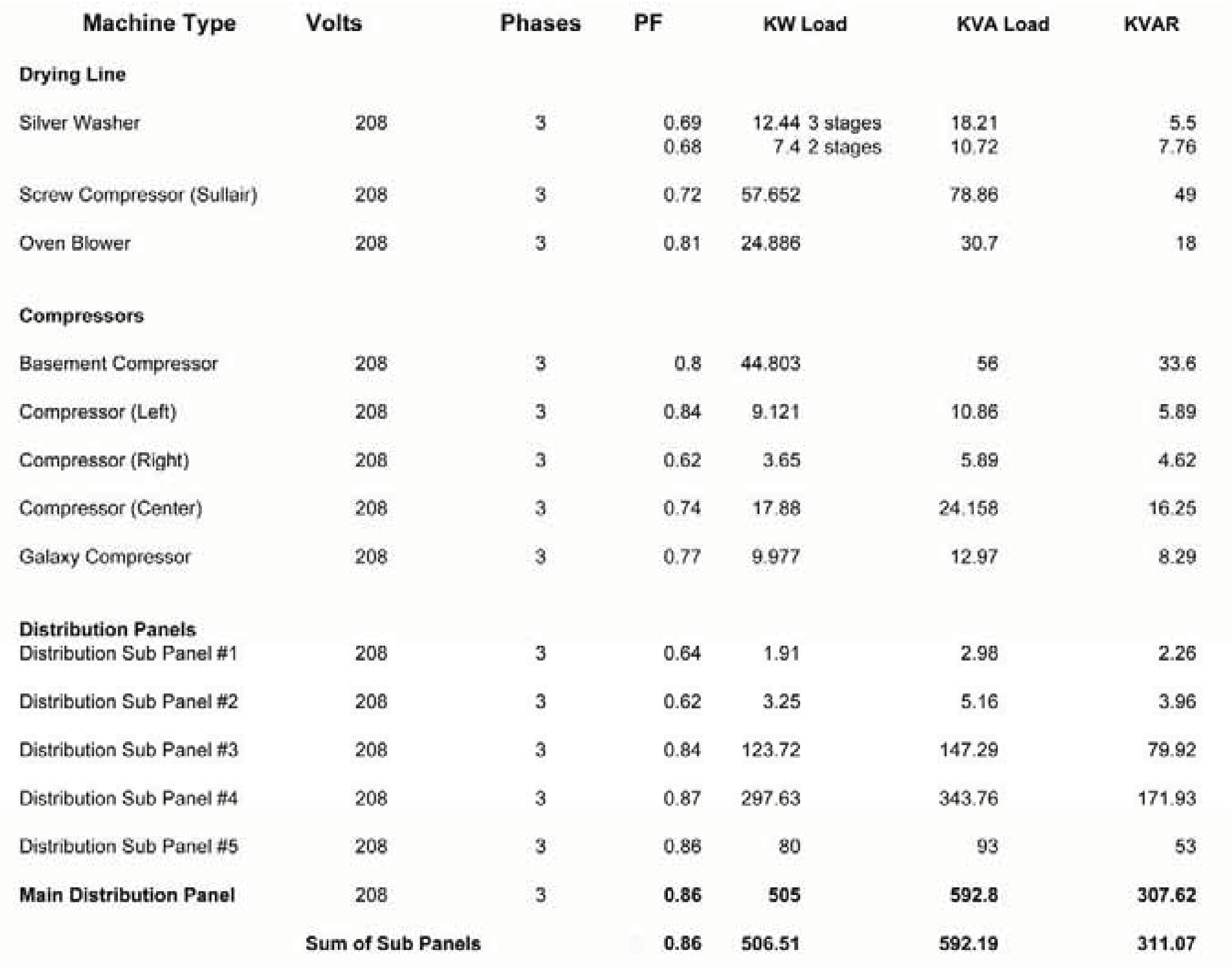
6 **Final Testing** : If the devices are properly sized, the power factor will have risen to the desired levels after installation. This will be confirmed by the data logger attached at the service entrance.

2.2 Results and Analysis

Results for two typical facilities will be documented in the following section. The first is a manufacturing facility with a peak demand of over 500-KW. The second is a supermarket with a peak demand of 150-KW.

2.2.1 500-KW Manufacturing Facility:

The facility had a peak load that varied between 500-KVA and 660-KVA with a peak KW load that varied between 425-KW and 550-KW. The VAR (Reactive) load was fairly consistent and varied between 300-Kvar and 330-Kvar, while the power factor varied between 0.82 and 0.86. Figure 5 lists the different equipment and their reactive loads.



Machine Type	Volts	Phases	PF	KW Load	KVA Load	KVAR
Drying Line						
Silver Washer	208	3	0.69	12.44 3 stages	18.21	5.5
			0.68	7.4 2 stages	10.72	7.76
Screw Compressor (Sullair)	208	3	0.72	57.652	78.86	49
Oven Blower	208	3	0.81	24.886	30.7	18
Compressors						
Basement Compressor	208	3	0.8	44.803	56	33.6
Compressor (Left)	208	3	0.84	9.121	10.86	5.89
Compressor (Right)	208	3	0.62	3.65	5.89	4.62
Compressor (Center)	208	3	0.74	17.88	24.158	16.25
Galaxy Compressor	208	3	0.77	9.977	12.97	8.29
Distribution Panels						
Distribution Sub Panel #1	208	3	0.64	1.91	2.98	2.26
Distribution Sub Panel #2	208	3	0.62	3.25	5.16	3.96
Distribution Sub Panel #3	208	3	0.84	123.72	147.29	79.92
Distribution Sub Panel #4	208	3	0.87	297.63	343.76	171.93
Distribution Sub Panel #5	208	3	0.86	80	93	53
Main Distribution Panel	208	3	**0.86**	**505**	**592.8**	**307.62**
	Sum of Sub Panels		**0.86**	**506.51**	**592.19**	**311.07**

Figure 5 – Equipment Loads, 500 KW Facility

Based on the 506-KW building load, the 310-Kvar reactive load, and the power factor of approximately 0.83, it would require 145-Kvar of added correction to achieve a final power factor of 0.95, 180-Kvar of added correction to achieve a final power factor of 0.97, and 235 Kvar of added correction to achieve a final power factor of 0.99. While it would require an additional 35-Kvar to achieve an additional 2% efficiency improvement from 0.95 to 0.97, it would require 55-Kvar (57% more) to get a further 2% improvement from a power factor of 0.97 to a power factor of 0.99. This is an example of the diminishing return and greatly increased cost of correction beyond 0.97 that was mentioned earlier.

The cost of an “At Load” correction system to achieve a power factor of 0.95 would be approximately $18,000, including engineering and installation. That is approximately $3,000 more than the equivalent service entrance correction system. The relative benefits of each type of system will be discussed later. As we were already on site implementing a correction system, an additional $2,000 would be required for the equipment and installation to achieve a power factor of 0.97, for a total cost of approximately $20,000. The advantage of the “At Load” system is that the line loss (KW) reduction in the building’s wires will help to pay for the system. With the service entrance system, there is no such savings as the line losses after the meter remain the same as before the system was added. There would only be savings if there is a reactive power charged assessed by the utility.

Using the “At Load” correction system, at the basement compressor we measured a four volt rise across all three phases with a 144 ampere load after correction. As the voltage at the service entrance remained nearly constant (+/- 1 volt) throughout our measurement period, it was apparent that the entire voltage drop was occurring on the wires within the building. Four volts at 144 amperes on a three phase service corresponds to a nearly **1000 watt reduction** in losses in the wires leading to that compressor from the service entrance. The savings will accrue for the entire time that the compressor is operating. At a 50% duty cycle for the screw compressor, operating twenty hours per day, that yields 10 KWH savings every day for the one machine, or approximately $2.00 per day in usage ($500/year). That does not include the reduction in demand charges related to that 1-KW reduction in load every month, which will save an additional $150 to $200 per year. Extrapolating those savings across the entire installed system, the load reduction will be in the range of 7-KW to 10-KW and the annual savings will be approximately $6,400 per year, excluding depreciation. With depreciation (35% tax bracket), the savings will rise to approximately $8,600 annually, resulting in a 2.3 year return on investment for the system. With a service entrance system, the energy savings will only be realized on the utility’s distribution system, and energy savings will not help to offset the cost of the installed equipment. The energy savings of the “At Load” system will be approximately 30,000-KWH annually, or approximately equivalent to the output of a 27.5-KW solar array. The cost for that array at current prices would be approximately $206,000, or over 10 times the cost of the power factor correction system. Tax credits on the solar array would be over $ 60,000, or more than three times the cost of the entire power factor system. The 2.3 year return on investment for the power factor correction system includes no public subsidies or tax credits of any kind. Figure 6 shows the KW, KVA, Kvar, and Power Factor at the service entrance of the 500-KW facility. The Power factor has been multiplied by one one million so that it would display on the same scale. Before we started activating the correction devices on Friday, March 19, the power factor was 0.82. When we finished on Monday, March 22, the power factor was 0.97. No work was done over the weekend. The entire system was installed by two electricians in approximately three days. Figure 8, shows the waveform for one of the compressors before it was corrected. Note the power factor of 0.79.

Prior to the installation of the equipment, the harmonic voltage distortion was measured at 2.67%. This rose to 2.91% after the installation was completed, an increase of less than a 0.25%, despite the addition of 180-Kvar of capacitance. This is documented in figure 7.

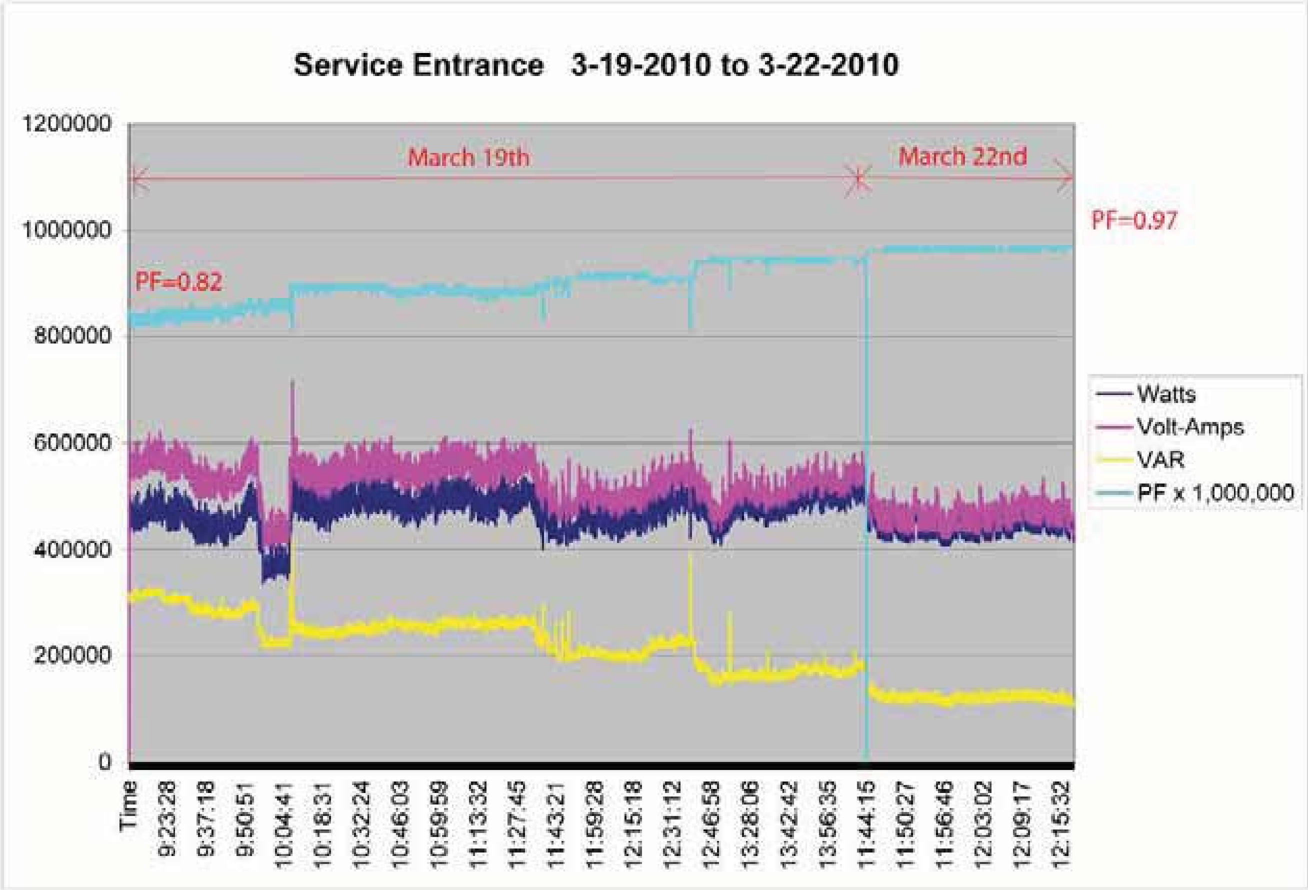


Figure 6 – KW, KVA, Kvar, and Power Factor during turn on of the correction system 180-Kvar of correction was added to raise the power factor from 0.82 to 0.97. Building loads will be reduced by 7-KW to 10-KW as a result of lower currents and the associated reduction in line losses.

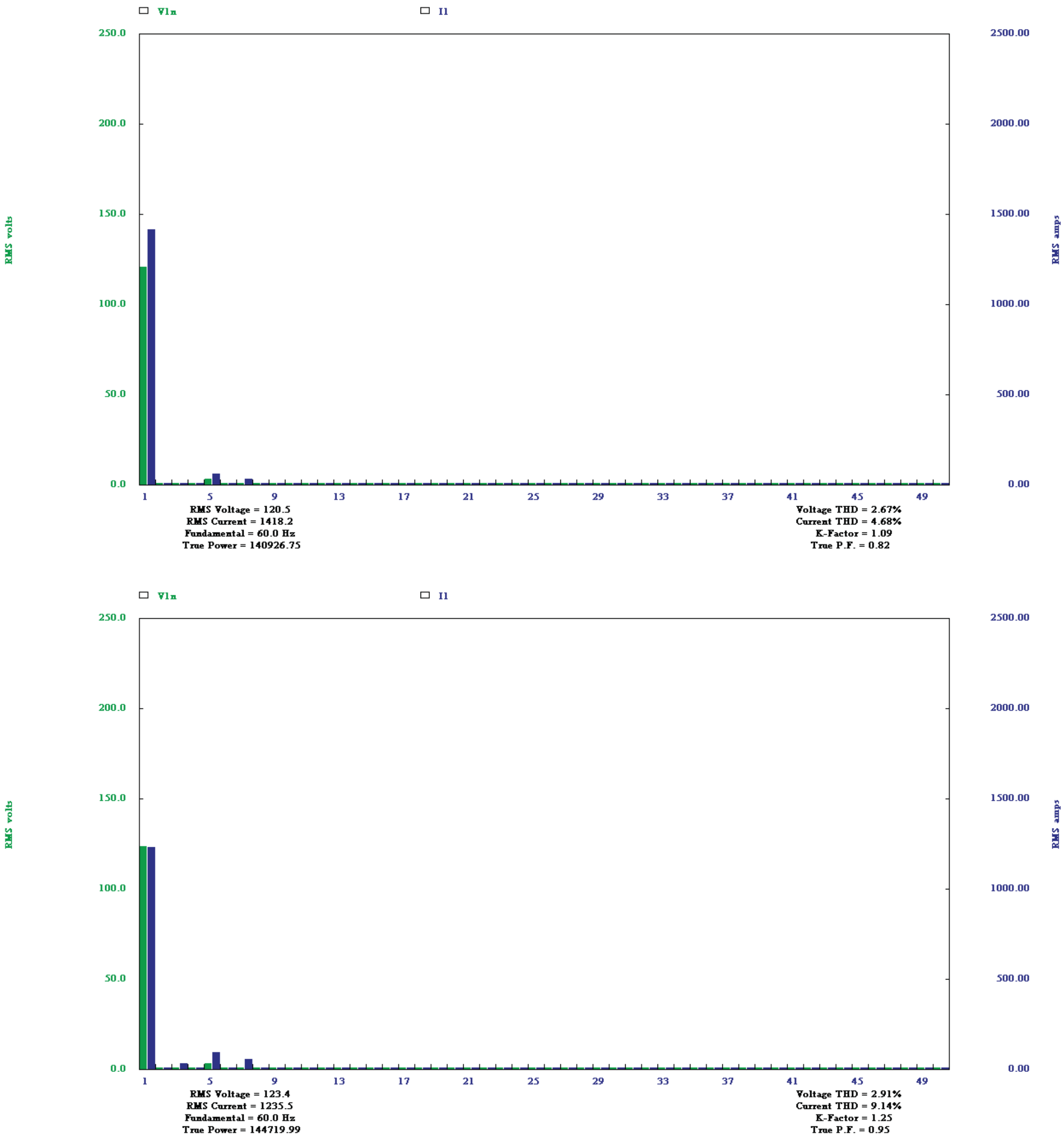


Figure 7 – Harmonics at the service entrance (500-KW facility), before and after correction. Increase in voltage %THD is less than 0.25% after the installation of 180-Kvar of Capacitance. Increase occurs primarily in the 5th and 7th harmonics, with a small increase in the 3rd harmonic.

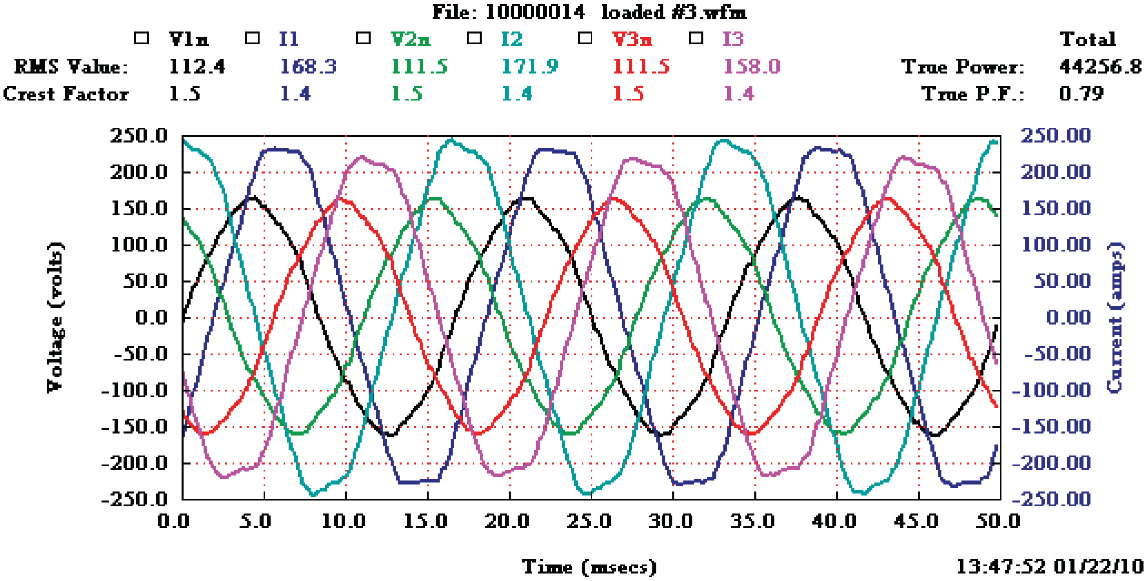


Figure 8 – Waveform of an uncorrected compressor with a power factor of 0.79. After correction, the power factor was raised to 0.96.

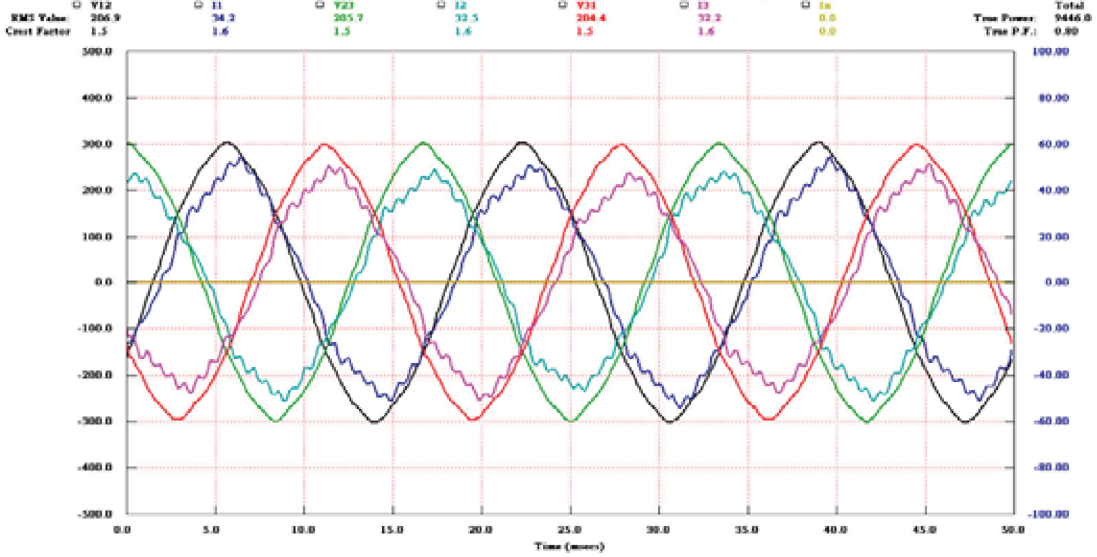
2.2.2 150 KW Peak Load Supermarket

The second commercial facility to be analyzed is a supermarket with a peak load of approximately 150-KW. Correction was added to all of the refrigeration compressors that were mounted in a central rack type arrangement. Correction was also added to the rooftop air conditioning. As the refrigeration operates with a nearly 100% duty cycle, the savings will be substantial, when measured over an entire year. Measurements were taken during the summer. Figure 9 documents the service entrance in October. As in the earlier graph, the power factor has been scaled to be visible on the graph. The scaling factor for this graph was 100,000. The initial power factor measured 0.93 before correction and was between 0.99 and 1.00 after correction. The refrigeration operates with an average 80% duty cycle. Figure 10 documents the before and after waveforms for one of the seven compressors that was corrected. The reduced currents resulting from the Power Factor correction will result in approximately a 1.25-KW reduction in line losses within the building during the winter months and a 2.5-KW reduction in losses during the summer cooling season. The result is that there will be a savings of nearly 11,400-KWH annually plus a minimum of a 1-KW reduction in demand. The total annual savings on energy costs will be approximately $2,400 per year. The entire system cost $12,000, including installation and engineering, resulting in a five year return on investment, before depreciation. If depreciation is considered (35% tax bracket), the return on investment is reduced to less than four years. The annual energy saved is equivalent to the output of a 10,400 watt solar array.

That array would cost approximately $77,000 at today's prices, or 6.5 times more than the reactive power correction system. The solar array would be eligible for over $25,000 in tax credits and $30,000 in rebates. Together, that is more than four and a half times the entire cost of the reactive power system. The harmonics distortion at the service entrance was lower after correction (1.74%) than before correction (1.93%), indicating that there were other devices present that caused more voltage distortion than the correction system.

Figure 9 – KW, KVA, Kvar, and Power Factor during turn on of the correction system 35-Kvar of correction was added to raise the power factor from 0.93 to 0.99. Building loads will be reduced by 1.25-KW during the winter and by approximately 2.5-KW during the cooling season as a result of lower currents and the associated reduction in line losses.

Before Correction - I avg=33 amperes, PF=0.8



After Correction - I avg=24 amperes, PF=0.99 (28% current reduction)

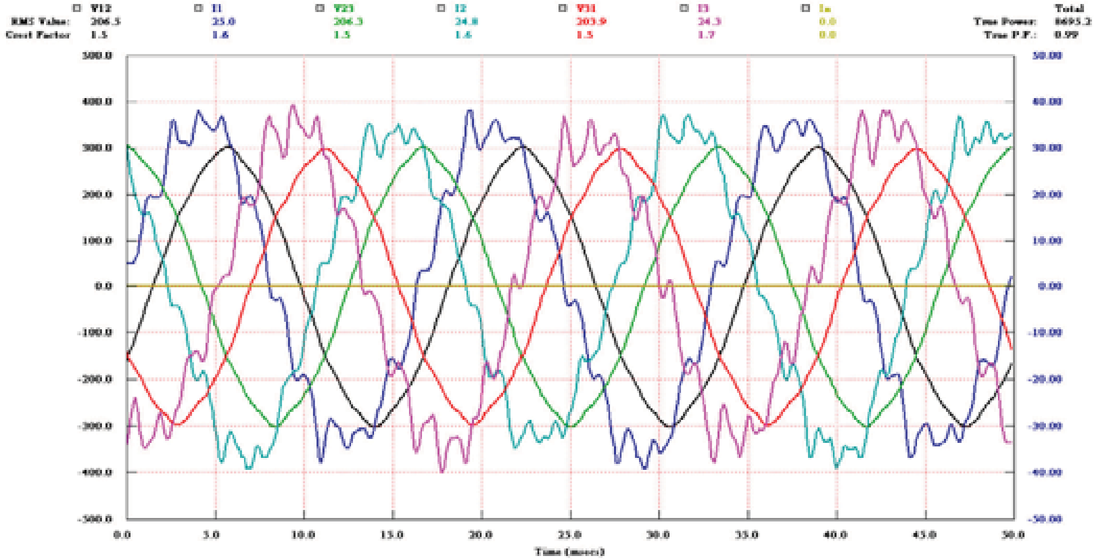


Figure 10 – Before and after waveforms for one of the seven compressors at the supermarket. I_{AVG} was reduced by 28% from 33 amperes to 24 amperes, while the power factor was raised from 0.8 to 0.99. That results in a 48% reduction in associated line losses.

2.3 Cost Benefit Analysis – Industrial and Commercial

We will be making the following assumptions in performing the financial analysis based on figures for the Con Ed service area :

- $2000 per KW to construct generation
- 13$-KVAR to install capacitance at the substation[5]
- $ .05-KWH wholesale electricity price, $ .20-KWH retail electricity price

2.3.1 500-KW Facility

In addition to the "after the meter savings" documented earlier for the 500-KW facility, that resulted in a return on investment for the customer of less than three years, there are also utility system savings. The low end, seven KW, load reduction will save approximately $14,000 in generation and the 180-Kvar of capacitance will alleviate the need for $2,350 worth of capacitance at the substation, for a system-wide savings of $16,350. That does not consider the additional savings of having a more lightly loaded distribution system and the ability to defer adding capacity. There are additional energy savings on the distribution system resulting from the reduction of thermal losses on the utility's conductors. As stated earlier, reactive copper losses on the distribution system account for approximately 0.32% of all power distributed, averaged over the year. The percentage is higher in the summer when the conductors are hotter. On a 600-KVA facility, that amounts to approximately 1-KW for the entire time that the facility is operating, or about 100 hours per week. That calculates to 5200-KWH annually, or an additional $260 worth of electricity at wholesale prices, for a total system wide, before the meter, savings of over $16,300 in the first year. When viewed from a societal perspective, the total additional cost of the system is less than $3,700, after subtracting generation costs, substation costs, and energy costs. That results in a return on investment of approximately six months, when considering the customer premise savings of $6,000 annually.

2.3.2 150-KW Facility

The utility system savings for the 150-KW facility are the 2.5-KW generation offset of $5,000, the 35-Kvar offset of substation capacitance of $450, and the energy reduction of 0.3%, or approximately 300 watts continuously (2628-KWH annually), which is $130 at wholesale prices. That totals to $5,580 resulting in the net cost of the system being reduced to $6,420. With a $2,400 after meter annual savings, the return on investment is less than 2.7 years, excluding depreciation.

---

[5] New York Independent System Operator (NYISO), Benefits of Adding Capacitors to the Electric System, February 27, 2008, PP.14

2.3.3 Additional Observations

The required period for the return on investment rises as the systems decrease in size. As can be seen from the earlier analysis, they are very cost effective in facilities above 100-KW. Still, when this technology is compared to other "Green" technologies, the return on investment is much shorter. This is also true for the smaller systems at locations using less than 100-KW of peak demand, even without government tax credits and rebates. The earlier cost analysis is based on aftermarket correction of customer premise equipment. It is very unfortunate that the government is not mandating the needed efficiency standards in the new equipment, where it would be far less expensive to implement. The additional cost of the equipment would be offset by energy savings in a matter of months. The full analysis of this and a more detailed comparison of the various costs appear in section 7.0.

Our analysis has not addressed the additional environmental benefits of reduced energy usage, nor the geo-political aspects of reduced energy usage. Nevertheless, simply on an economic basis, the cost effectiveness of this technology justifies its implementation.

2.4 Conclusions

Based on our measurements and results obtained measuring the electrical characteristics of industrial and commercial locations, we have come to the following conclusions:

- The power factor is sufficiently low in industrial and commercial equipment that improving it will result in a substantial energy savings throughout the entire utility system, when measured in KWH.

- We can cost effectively improve the power factor for existing equipment. The return on investment is between two and four years at present, including depreciation, and not including Kvar charges. The return on investment will be shorter if the utility charges for reactive power.

- "At Load" Power Factor Correction in this environment does not significantly increase the amount of harmonics present on the utility system.

- Power Factor Correction must be load based and must only operate when needed. Excess capacitance connected to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance would add extra impedance that would have to be energized, applying extra load to the system during a restart.

- In most applications, “At Load” correction has significant advantages over “Service Entrance” correction with respect to energy savings, cost, return on investment, and reduced levels of harmful harmonics.

- Standards need to be modified so that new commercial and industrial machines are designed with a high power factor as part of the design criteria.

While the last item on the list will increase the price of the equipment, as can be seen in figure 19, the accrued savings on energy will more than offset the additional cost.

PART 3 – REFRIGERATED VENDING MACHINES

3.0 Background and Conclusions – Refrigerated Vending Machines

This section addresses "At Load" power factor correction in refrigerated vending machines. Initially, this was not included in the scope of the work. We were out in the field with the equipment and decided to analyze a refrigerated vending machine. It had the worst power factor of any piece of equipment that we found. Upon further investigation, we determined that the machine we first tested was not an aberration but was in fact, the norm.

A report issued by Pacific Gas and Electric of California (PG&E) indicated that in 2002 there were three million refrigerated vending machines in the United States[6]. As of 2005, New York State represented 6.4% of the total US population. It would be fair to assume that approximately 6% of the refrigerated vending machines in the United States, or 180,000 machines, are located in New York. That provides a large "market" on which to implement this process. In addition, according to the PG&E document, the design life of the vending machines is ten years, so many that are currently in service will be there for many years.

While much of this documentation will reference the New York Metropolitan Area as the work was done here, it is applicable to other areas of the country as well. Conclusions that we have drawn from the work completed to date are the following:

- The power factor is sufficiently low in refrigerated vending machines that improving it will result in substantial energy savings throughout the entire utility system, when measured in KWH.
- We can cost effectively improve the power factor for existing refrigerated vending machines, using aftermarket devices.
- Standards need to be modified so that new refrigerated vending machines are designed with a high power factor as part of the design criteria.

---

[6] Codes and Standards Enhancement Initiative For PY2004: Title 20 Standards Development, Analysis of Standards Options For Refrigerated Beverage Vending Machines, Prepared for: Gary B. Fernstrom, PG&E, Prepared by: Davis Energy Group - Energy Solutions, May 5, 2004, PP. 2

- Power Factor Correction in this environment does not measurably increase the amount of harmonics.

- Power Factor Correction in this environment will reduce CO2 emissions by 21,000 tons annually for New York State.

- Power Factor Correction must be load based and must only operate when needed. Excess capacitance connected to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance would add extra impedance that would have to be energized, applying extra load to the system during a restart.

3.1 Implementation

Implementation of the Power Factor Correction for the vending machines was relatively simple and involved the following steps:

1 **Acquiring Funding**: This was provided through a NYSERDA grant to offset the cost of equipment that would be installed within customer premises.

2 **Equipment Measurement** : Upon confirming that we had project funding, we tested various devices to try to find equipment that would lend itself to cost effective Power Factor correction. After measuring the power factor of several refrigerated vending machines, we determined that they were a prime candidate for the project.

3 **Device Design** : While devices for power factor correction are readily available for large facilities, that is not the case for the smaller scale application that we are considering here. Labor and other installation costs have to be kept to a minimum in order to make this process viable. In the past, one of the reasons that small scale power factor correction has not been applied is installation cost. The bulk of that cost is in labor. After applying for the grant and prior to being approved for the grant, we designed and fabricated devices that could be installed by a non-technical person. No electrician is needed. A patent was filed on these devices, called PLIP's®, in November, 2008. PLIP® is an acronym for "Plug In Power Factor Correction". Figure 11 is a photo of a PLIP®. A specialized version of the PLIP® was developed to work with the vending machines. Its physical package is identical to the other versions.

4 **Implementation and Testing** : After receiving approval on the PLIP's® from Underwriters Laboratories, we started installing PLIP's® on various refrigerated vending machines. There are three major manufacturers of these types of machines in the United States and they supply 85% of the machines in use[7]. None of the machines that we tested had a power factor above 0.75 .

---

[7] Codes and Standards Enhancement Initiative For PY2004: Title 20 Standards Development, Analysis of Standards Options For Refrigerated Beverage Vending Machines, Prepared for: Gary B. Fernstrom, PG&E, Prepared by: Davis Energy Group - Energy Solutions, May 5, 2004, PP. 2

Figure 11: The PLIP® Plug In Power factor correction. Power Factor Correction Installation costs are greatly reduced. An unskilled person can install these.

Figure 12: A Dixie-Narco Vending Machine, The waveform for this machine appears in Figure 13.

3.2 Important Facts about Vending Machines that will affect an efficiency program

The head of the equipment division that manufactures vending machines for a major North American bottler told me that the Department of Energy only gives them credit for efficiency improvements that occur within the machine envelope. Power Factor improvement will reduce losses caused by the machine outside of the machine envelope. It would cost the bottler approximately ten dollars more per machine to implement the improvement, increasing the cost of the machine by approximately one-half of one percent. That would be a significant cost with the volume of machines that they manufacture, and the Department of Energy would not recognize the improvement and give them credit for it. To put the cost in perspective, if the correction were installed by the bottler, the customer that had the machine in its facility would realize the ten dollar savings in about one year. The utility would save that much, as well.

While learning about the electrical characteristics of vending machines, we also learned a great deal about the market for new and used refrigerated vending machines. This was accomplished by reading the available literature and doing web searches, but also by making phone calls to several vending machine companies and visiting Superior Vending Machine in Mt. Vernon, NY. Among things that were learned are:

1 -The service life for a new refrigerated vending machine is approximately ten years. It can be longer, depending on where it is located and how many times it is refurbished..

2 -A new refrigerated vending machine will cost between $3, 400 and $4,500, including shipping. As they are expensive, a program to retrofit existing machines will improve efficiency more quickly than a program to replace the machines.

3 - A used, refurbished, refrigerated vending machine will cost between $1,000 and $2,300 depending on the bottle capacity, including freight. When the machines are refurbished, they are sold with approximately a four month warranty. The compressors are usually “reworked” but are not usually replaced when the machines are refurbished. That results in vending machines having the compressors with the existing efficiencies remaining in use for an extended period.

4 -Refrigerated Vending machines use a 1/4-Horsepower compressor. Frozen food (Ice Cream) dispensing machines use a 1/3-Horsepower compressor. None of the machines that we tested had a power factor above 0.75. The larger vending machines that have more lamps in their display operate with a higher power factor because the compressor

is a smaller percentage of the total consumption. Still, the compressor discharges the same amount of reactive power (Vars) as the compressors on the machines with the lower power factor and a lower peak consumption. Similar results were seen from all brands of refrigerated vending machines. While Dixie-Narco and Pepsi vending machines are documented in the power consumption graphs, machines from Royal Venders Incorporated and the Vendor Company operated with a similar power factor.

3.3 Data Analysis

Figures 13, 14, and 15 show the before and after graphs from three vending machines that are representative of the various machines that were tested. On all of the machines, it can be seen that at least a two ampere reduction was achieved through the implementation of power factor correction. On average, a 2.2 ampere reduction and a 0.26-KVA reduction was achieved per machine. Extrapolated over 180,000 machines in New York State, that corresponds to a 46,800-KVA reduction in coincident peak demand and a 40,600-KVA reduction in continuous load on the distribution system based on an 87% duty cycle for the equipment. Still 3.6% of energy is lost annually as distribution losses, and 88% of that is copper loss, resulting in 3.2% of all losses being distribution copper losses. Applying that to the 40,600-KVA reduction in average demand results in a 1300-KW average reduction in required generation and a 1500-KW reduction in peak generation related to the reduced currents resulting from power factor correction. Using the figure of a 1300 KW average power reduction yields a net annual savings of 11,388,000-KWH annually in reduced losses on the distribution system. In addition to savings on the utility's distribution system there will also be significant savings on the customer's side of the meter within the customer premises. This will occur because of reduced heating within the premise's wiring that is manifested as KWH on the utility bill. Measurements that we have taken at industrial locations indicated that raising the power factor from .7 to .96 can reduce KWH loss by as much as 5% to 7% within customer premises. A lower initial power factor will yield more dramatic KW savings resulting from power factor correction. The power factor of refrigerated vending machines is sufficiently bad that large KW reductions can be achieved through correction.

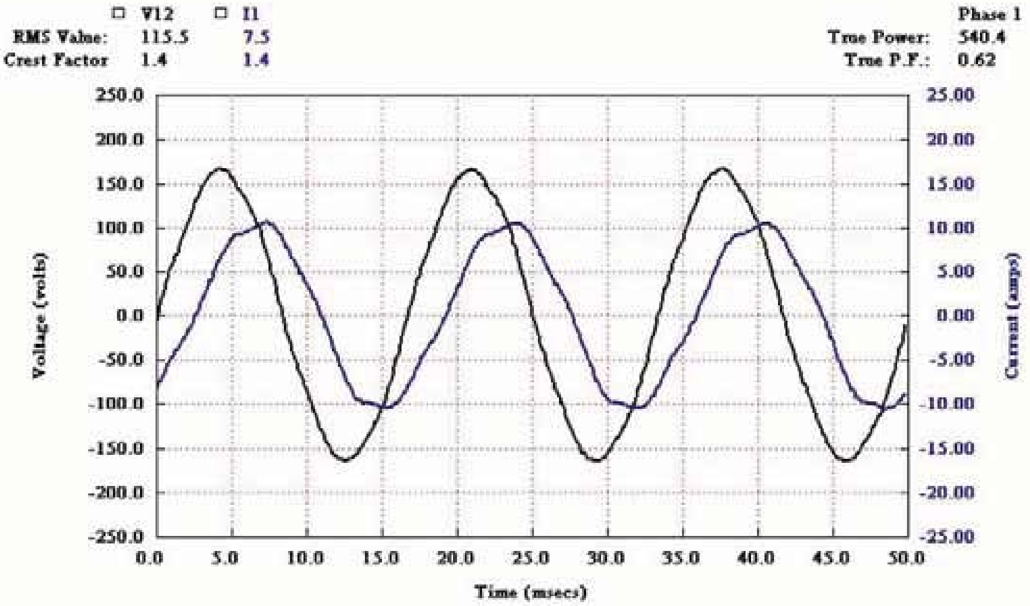
To test this concept we used a 120 Volt motor that operated at 4.65 amperes, within the current range of a refrigerated vending machine. We plugged it in to several receptacles throughout a five year old building, wired during 2004 to the electrical code being used at that time. As the building is relatively new, oxidation levels on the electrical components will be at a minimum. The building has approximately a 5000 square foot footprint and a 400 amp service that was only delivering approximately 18 amps per phase at the time of the tests. The receptacles were connected by approximately fifty feet of #12 wire to 15 amp circuit breakers in a sub panel. (50 feet of #12 copper wire will have a resistance of approximately 0.1 ohms.) That was in turn wired to a 200 amp circuit breaker in a main panel near the building service entrance. Because of the low building current at the time of the tests and the large size of the service relative to the 4.65 amp motor current, nearly all of the voltage drop would have occurred at the circuit breakers, within the 12 gauge wire, and the receptacle-plug interface. A 1.4 volt drop at a 4.68 amp current indicates a circuit resistance of approximately 0.3 ohms. For the Dixie-Narco machine, the waveform for which is shown in figure 14, the I^2R line losses within the building before correction, with an 8.4 amp current and a 0.3 ohm circuit resistance, would be 21.17 watts (8.4 x 8.4 x 0.3). After correction, with the current at 6.3 amperes, the line losses would be 11.9 watts (6.3 x 6.3 x 0.3) . The correction would yield a reduction of 9.27 watts on a circuit with a resistance of .3 ohms. In an older building, with increased levels of oxidation on the wire interfaces, the resistance and associated thermal losses could be considerably higher. Furthermore, refrigerated vending machines are primarily located in commercial buildings that could have much larger footprints than 5000 square feet. That would make the circuit lengths longer than fifty feet and increase the circuit resistance. While the after meter line loss savings for some machines may be less than 9-watts, the average age of the building stock in New York is also considerably older than five years. That would result in higher circuit resistances than the 0.3 ohms that we measured. Considering the variables of circuit length, circuit age, and the different machine capacities, the 9.27-watts is a reasonable average for after meter line losses, as they relate to refrigerated vending machines.

Based on the 425-watt average power consumption of the vending machines listed in the PG&E paper, 180,000 machines would consume 76,500-KW. A 2.2% reduction in customer premise losses, less than half of what we have previously measured at industrial locations, would yield a reduction of 1669-KW in required generation for losses incurred within customer premises. A 9.27-watt savings per machine on 180,000 machines would yield the same 1669-KW savings. The annual energy savings would be 14,620,440-KWH annually.

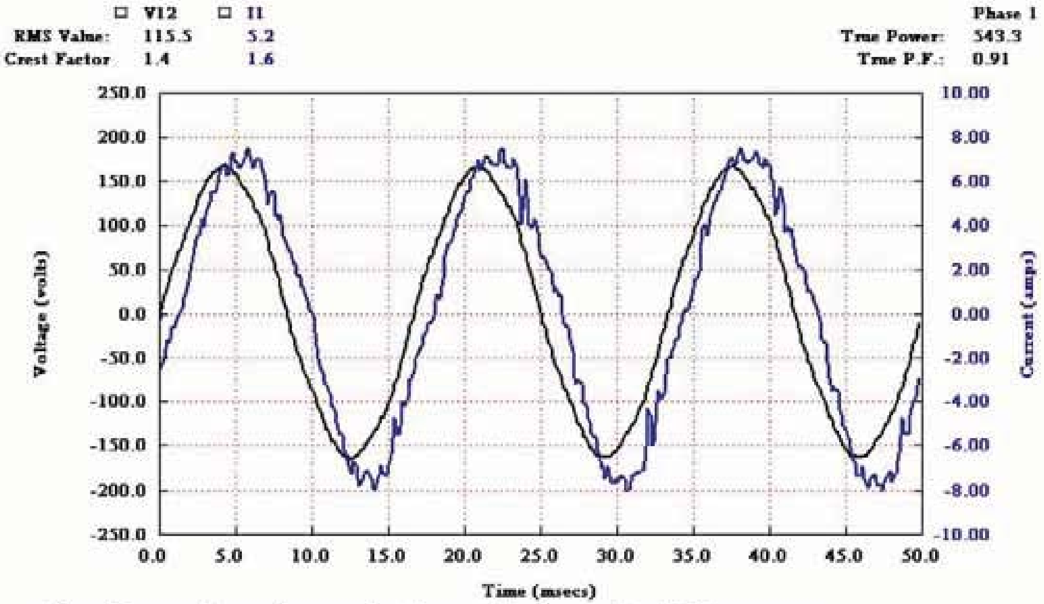
Based on efficiency improvements achieved on both the distribution system and within the customer premises as a result of “At Load” Power Factor Correction, the total savings for New York State are:

- 3,170-KW Reduction in required generation
- Minimally, a 26,008,440 annual reduction in KWH that includes 11,388,000-KWH on the utility’s distribution system and 14,620,440-KWH within the customer premises

In addition, our measurements indicated that the Power Factor Correction may raise the Total Harmonic Distortion of the current waveform by approximately 1%. At such a low level, the minimal increase in harmonics does not contribute a negative effect on the system.

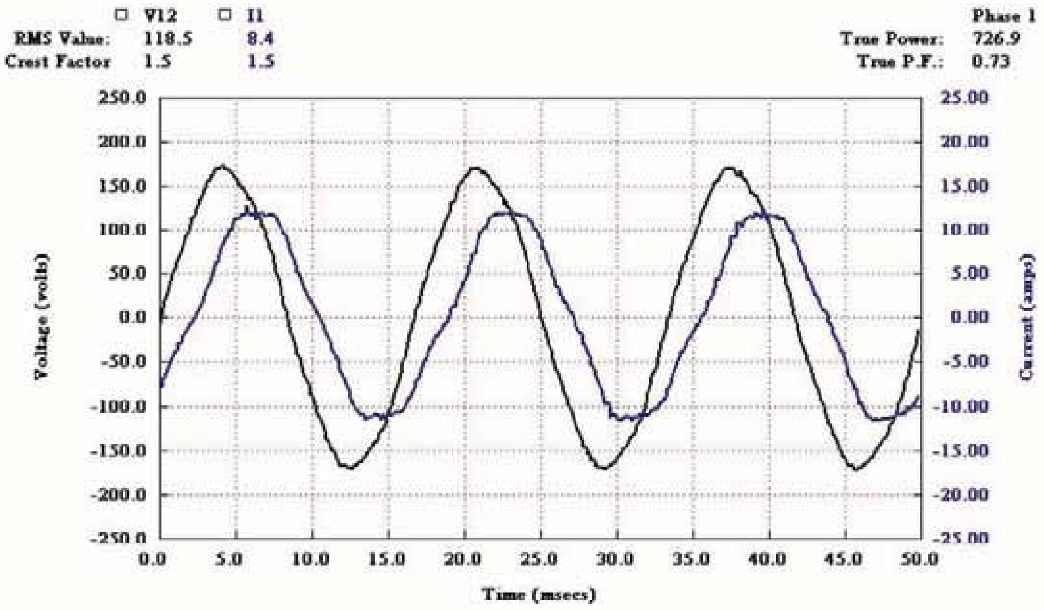


Before Correction - Power Factor =.62, Current=7.5 Amperes

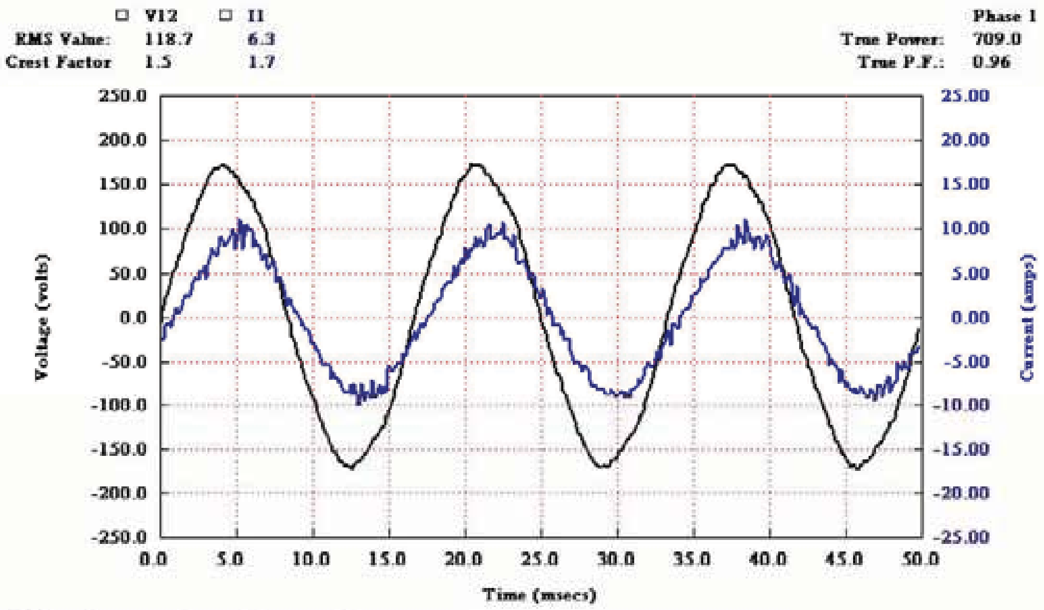


After Correction - Power Factor = .91, Current =5.2 Amperes
31% Current Reduction, 51% reduction in associated line losses

Figure 13: Before and after waveforms from a Dixie-Narco vending machine. A 2.3 ampere (31%) current reduction was achieved through the use of power factor correction.

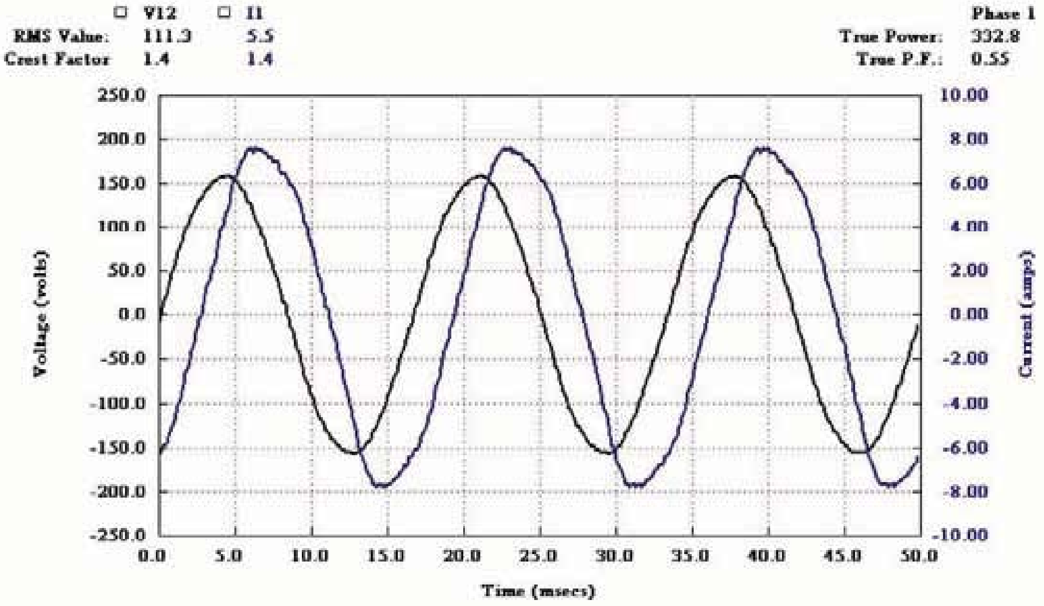


Before Correction - Power Factor = .73, Current=8.4 Amperes

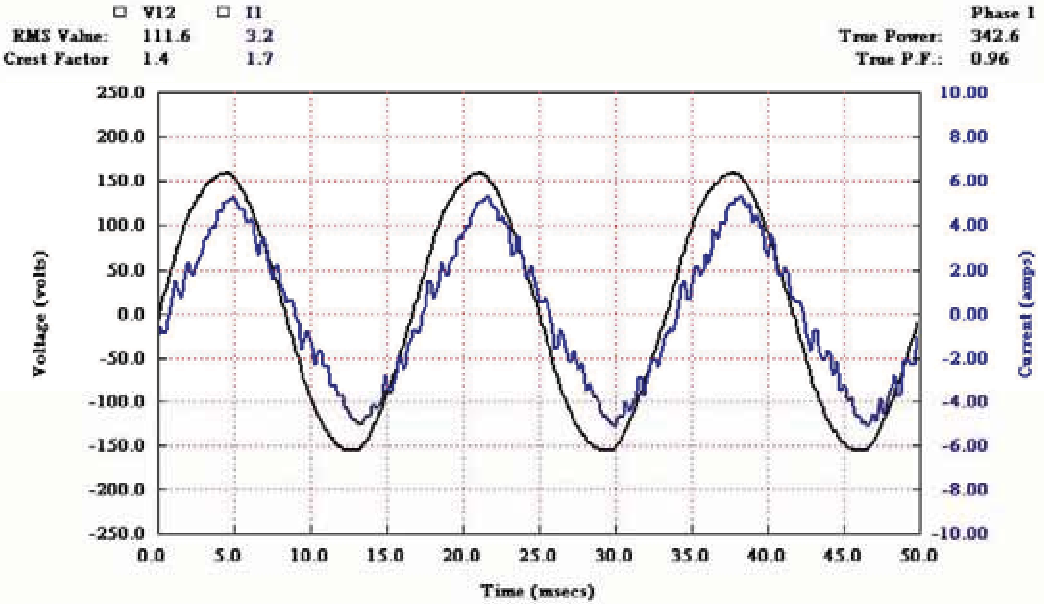


After Correction - Power Factor=.96, Current=6.3 Amperes
25% Current Reduction , 43% Reduction in associated line losses

Figure 14: Before and after waveforms from a Dixie-Narco vending machine. A 2.1 ampere (25%) current reduction was achieved through the use of power factor correction.



Before Correction - Power Factor =0.55, Current = 5.5 Amperes



After Correction - Power Factor =0.96, Current =3.2Amperes
42% current reduction , 66% reduction in associated line losses

Figure 15: Before and after waveforms from a Pepsi® High Visibility vending machine. A 2.3 ampere (42%) current reduction was achieved through the use of power factor correction.

3.4 Cost Benefit Analysis

We will be making the following assumptions in performing the financial analysis based on figures for the Con Ed service area :

- $2,000 per KW to construct generation
- 13$-KVAR to install capacitance at the substation[8]
- $ 70 cost for a PLIP®. This is higher than what the cost will be if it is mass produced.
- 180,000 PLIP® ‘s will contain approximately 100,000-KVAR of capacitance.
- 26,008,440 annual reduction in KWH that includes 11,388,000-KWH on the utility’s distribution system and 14,620,440-KWH within the customer premises
- 3,170-KW reduction in necessary generation
- $ .05-KWH wholesale electricity price, $ .20-KWH retail electricity price

Using the figures above, the cost for 180,000 PLIP®‘s would be $ 12,600,000 and the savings are as follows:

One time cost offsets

• Reduced generation (3170-KW @ $ 2000-KW)	$6,340,000
• Reduced cost of capacitance at the substatio	$1,300,000
	$7,640,000

Annual cost offsets

• Reduced annual consumption (wholesale price)	$1,300,422

Based on a $12,600,000 project cost, the Return on Investment (ROI) would be 3.8 years if the utility implemented the program. The figures above do not factor in reduced costs for reduced maintenance of the system because of reduced load, both within customer premises and on the utility’s portion of the system. While the reduction at each location is fairly small, these machines are very prevalent and reducing their combined effect on certain areas of the system could be the difference in portions of the system surviving a day of very high load.

---

[8] New York Independent System Operator (NYISO), Benefits of Adding Capacitors to the Electric System , February 27, 2008, PP.14

In addition to savings on the utility system, the savings to the customer would be as follows:

(14,620,440-KWH x $.20)/180,000 machines = $ 15.84 per machine/yea.

If the utility customers purchased the devices, the Return on Investment (ROI) to improve the power factor on a vending machine would be approximately four years on a machine with a lifespan of ten years or more.

In addition to the short ROI for the equipment there are environmental benefits, as well. On average, every KWH of electric generation in the United States results in 1.5 pounds of CO2 emissions. The 26,008,440 annual reduction in KWH in New York State would result in a minimum reduction of over 19,500 tons of CO2 emissions annually. Those reductions cannot be achieved with capacitance installed at the substation.

If the standards for these machines were tightened to mandate a high power factor, the cost of a $4,000 machine would increase by approximately $20. Nevertheless, as the numbers above indicate, that amount would be recouped by the customer in approximately one year.

3.5 Conclusions

Based on our measurements, and results obtained measuring the electrical characteristics of refrigerated vending machines, we have come to the following conclusions:

- The power factor is sufficiently low in refrigerated vending machines that improving it will result in substantial energy savings throughout the entire utility system, when measured in KWH.

- We can cost effectively improve the power factor for existing refrigerated vending machines.

- Power Factor Correction in this environment does not measurably increase the amount of harmonics.

- Power Factor Correction in this environment will reduce CO2 emissions by a minimum of 19,500 tons annually for New York State.

- Power Factor Correction must be load based and must only operate when needed. Excess capacitance connected to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance would add extra impedance that would have to be energized, applying extra load to the system during a restart.

- Standards need to be modified so that new refrigerated vending machines are designed with a high power factor as part of the design criteria.

While the last item on the list will increase the price of the equipment, the accrued savings on energy will more than offset the additional cost.

PART 4 – MULTI-FAMILY RESIDENTIAL

4.0 Background and Conclusions - Multi-Family Residential

This section presents the results of applying “At Load” power factor correction to multi-family dwellings.

A 1991 census stated that there were between 17,000 and 20,000 buildings of 50 or more units within New York State. That provides a large “market” on which to implement this process. While much of this documentation will reference the New York Metropolitan Area as the work was done here, it is applicable to other areas of the country as well.

Conclusions that we have drawn from the work completed to date are the following:

- The power factor is sufficiently low in the multi-family environment that improving it will result in substantial energy savings throughout the entire utility system, when measured in KWH.
- We can cost effectively improve the power factor for existing apartment buildings in the near term.
- Standards need to be modified so that new multi-family buildings are designed with a high power factor and a balanced load as part of the design criteria. Compliance should be verified prior to a Certificate of Occupancy being issued.
- Standards need to be modified so that new appliances are required to have a high power factor as part of the design criteria. This includes refrigeration and, especially, air conditioners. Some of the newer 220 volt air conditioners operated with a power factor near 0.99. None of the 120 volt air conditioners operated with a power factor above 0.92, including the newest units that were less than a year old. Most of the measurements were taken on hot days, so the units would have been operating as efficiently as possible.

- Standards need to be modified so that new appliances and other electrical devices to be attached to the utility have more strict limits on the amount of electrical harmonics that they generate per watt of consumption. In particular, this will apply to computers, televisions, and fluorescent lighting. Harmonics, oscillations induced in the electrical power system, adversely affect electrical efficiency. Furthermore, harmonic mitigation can be very costly to implement.

- Power Factor Correction in this environment does not measurably increase the amount of harmonics measured at the utility transformer.

- Power Factor Correction must be load based and must only operate when needed. Excess capacitance connected to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance would add extra impedance that would have to be energized, applying extra load to the system during a restart.

4.1 Implementation

Implementation of the Power Factor Correction Project involved several steps.

1. **Acquiring Funding**: This was provided through a NYSERDA grant to offset the cost of equipment that would be installed on utility poles or within customer premises

2. **Coordination with the utility** : As we were attempting to determine the aggregate effect of "At Load" power factor correction, it was essential to perform measurements at the secondary (low voltage side) of the utility distribution transformer. Consolidated Edison was extremely cooperative in this regard. It provided the funding and the personnel to install the power monitors on the utility poles. After consulting with Con Ed about the requirements, we designed and built power monitors that were mounted by Con Edison personnel on the poles. After we chose a neighborhood, they also assisted with choosing transformers that would be optimal in achieving our goal.

3. **Test Sites:** We needed utility customers who would be willing to participate in a trial of this type. We were fortunate because the residents of Hilltop Terrace were very willing participants. It is a true leap of faith for homeowners with a non-technical background to let a stranger into their home to correct a reactive power "problem" that they didn't even know existed. In addition to having cooperative residents, Hilltop Terrace was ideal in that it was fairly typical of much of the housing stock in the New York area. It is a garden apartment complex that was built circa 1965. As there are 80 units in five buildings, serviced by one transformer, the data will also be fairly representative of a 40 to 200 unit dwelling without central air conditioning, scaled for the number of units. There is a mix of one, two, and three bedroom units. Air Conditioning consisted of 120 volt and 220 volt air conditioners mounted in "through-the-wall" sleeves. The first complex that we sought to use for the trial did not want to participate. It was a complex of rental units. The landlord had little incentive to participate, as they did not pay the utility bills for the apartments. In contrast, Hilltop Terrace is a cooperative where the tenants own the apartments.

4. **Power Monitors:** The essential part of any project of this type is having accurate data. We designed and built a monitor with more capability than we thought we would need. Our reasoning was that it would be far easier to ignore unneeded data than to collect extra data from a meter that didn't have the capability. As such, each monitor collects several hundred electrical parameters and three temperature parameters and transmits them to a collection

hub twice each minute. Monitored electrical data includes voltage, current, frequency, power (KW), reactive power (KVAR), apparent power (KVA), power factor, harmonic distortion, and both voltage and current harmonics to the fortieth harmonic. Data is available both in aggregate for the three phases or by individual phase. Figure 16 is a photo of the monitor installations at Hilltop. Temperatures were recorded for the transformer, the power monitor, and the ambient air temperature. In addition, we have access to the data for a nearby solar array. This allowed us to compare the instantaneous solar load with the device temperatures. Split Current Transformers were used to measure current. This sacrificed approximately 2% in accuracy, however it let us attach the monitors without interrupting service, a requirement for Con Edison.

5 **Wireless Network and Data Hubs**: To easily and efficiently collect the data from the remote locations, we added wireless capability to the power monitors. The monitors were set up as a wireless mesh, where each wireless device can act as a transmitter/receiver or a repeater. Each group of monitors feeds back to a computer hub that collects and stores the data. It will also display the measured parameters for each monitor in the group. The hubs connect back to a central computer via a hardwired data link. The data is fully analyzed and collated at the central location. Figure 17 shows the locations of the two monitors, repeaters, and data collection hub for this portion of the project.

6 D**ata Base Design**: A data base had to be designed to format the large quantities of collected data for easy retrieval. Each monitor group will generate between 15 megabytes (MB) and 30 MB of data in a 24 hour period, depending on how far apart the monitors are and how many “hops” the data has to make from monitor to data hub.

7 **Device Design**: While devices for power factor correction are readily available for large facilities, that is not the case for the smaller scale application that we are considering here. Labor and other installation costs have to be kept to a minimum in order to make this process viable. In the past, one of the reasons that small scale power factor correction has not been applied is installation cost. The bulk of that cost is in labor. After applying for the grant and prior to being approved for the grant, we designed and fabricated devices that could be installed by a non-technical person. No electrician is needed. A patent was filed on these devices, called PLIP’s®, in November, 2008. PLIP® is an acronym for “Plug In Power Factor Correction”. Figure 18 is a photo of a PLIP®.

Monitor 10 Monitor 11

Figure 16: Pole Monitors at Hilltop Terrace. Monitor 10 services one building at Hilltop Terrace and a second building in a different complex. Monitor 11 services five buildings at Hilltop Terrace. The transformer at Monitor 10 is a 75 KVA, 3 phase transformer. The transformer at Monitor 11 is a 150 KVA, 3 phase transformer. Both transformers date to the construction of the complex in 1965.

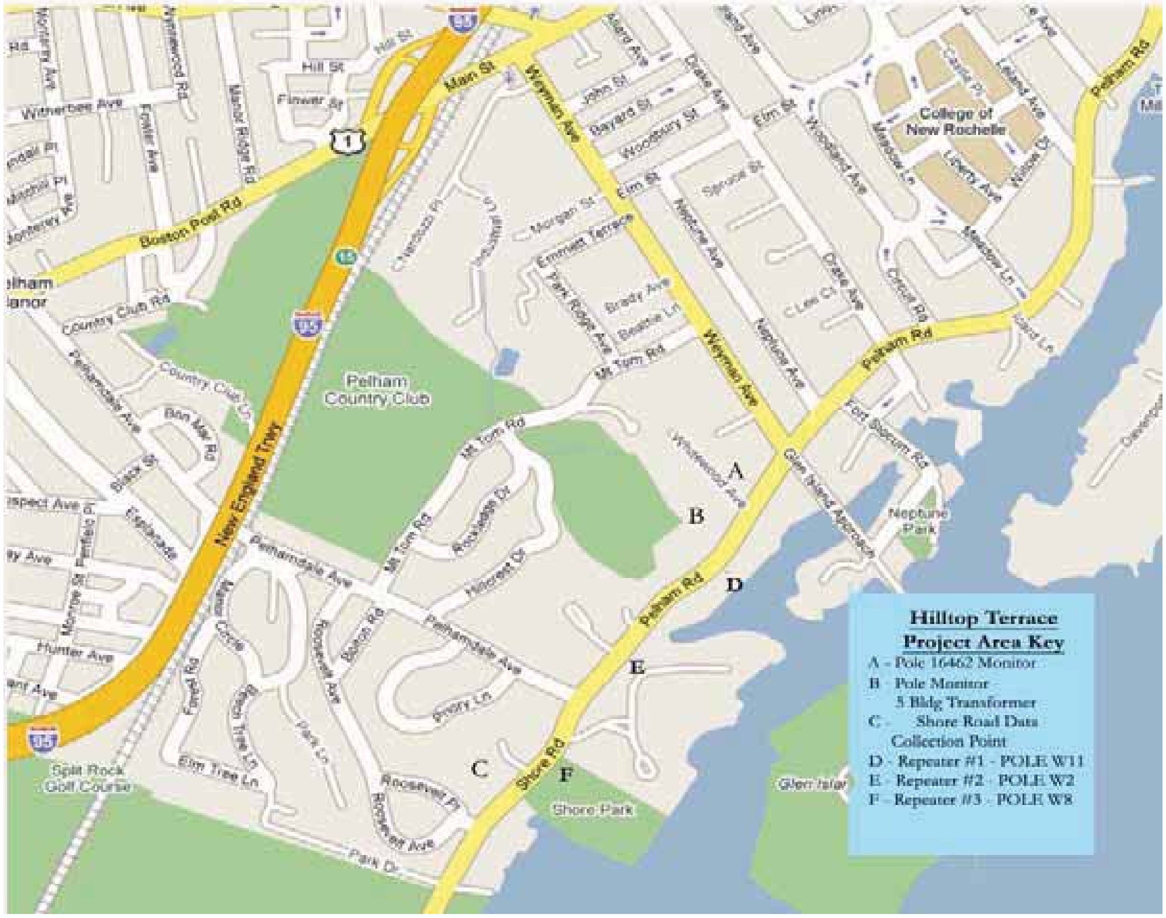


Figure 17: Hilltop Terrace Monitor, Repeater, and Hub Locations
The distance between A and C is 0.55 Miles.

Figure 18: The PLIP® Plug In Power factor correction. Power Factor Installation costs are greatly reduced. An unskilled person can install these. After three days of taking measurements, we knew on sight which pieces of equipment needed correction.

4.2 Observations about customer behavior and the service area that affect energy efficiency and related Programs

While learning about the electrical characteristics of customer premise equipment, we also learned a great deal about the service area, customer behavior, and obstacles to implementing electrical efficiency programs of this type. Among things that were learned are:

1 Utility customers will not replace air conditioners until they cease to function. Many of these units are inserted through sleeves in the wall. Most of the newer, replacement air conditioners are smaller and don't fit the sleeves without some adaptation. This retrofit can be costly and time consuming. In addition, the older units are cumbersome and it is easier to leave them there until they no longer work, despite the lower operating costs of the newer units. During the course of the project, we did not encounter a single person with a new air conditioner that had purchased it before the old one ceased to function properly.

2 Rental units present a different problem as most landlords, responsible for replacing the appliances, don't pay for the electricity to operate them. In one complex that we looked at, there were over two hundred apartments with approximately four hundred fifty air conditioners. To replace all of them would have cost over $225,000. There were air conditioners operating there that dated to the 1960s. It was at this complex that we encountered the "What's in it for me?" syndrome. That was despite the fact that the work that we were proposing would have cost the landlord absolutely nothing except providing access.

3 In a legacy building on Central Park West in Manhattan, which only has window mounted air conditioning units at present, they have a program to insert sleeves into the walls to remove the units from the windows. Each new sleeve costs approximately $6,000 without the associated air conditioner. The cost is a deterrent to participating in the project. Many residents are maintaining the status quo and keeping their old units.

4 Scheduling a convenient time to meet with the customer is one of the biggest obstacles in the process.

5 Manufacturers of newer 120 volt air conditioning units (manufactured within the past two years) have done little to nothing to correct the power factor of their appliances. Those 120 volt units operated with a power factor between 0.88 and 0.92. The newer 220 volt air conditioners operated with a power factor of 0.98 to 0.99. Older air conditioners that we measured at either voltage operated with a power factor between 0.80 and 0.92.

6 Aesthetics are important when you are going to attach an energy saving device within a utility customer's home, no matter how small the device is.

7 A load imbalance was not apparent in the data for Hilltop Terrace so it will not be discussed in the analysis. Nevertheless, load imbalances were measured on other monitors that we installed. This is caused by locating too many active circuit breakers on one phase of the service and too few circuit breakers on another phase. During periods of heavy load in the summer, half of the transformer will operate near capacity, while half will be lightly loaded. If there is excess current in part of the transformer and one leg is operating near capacity, it will get warmer and operate with less than optimal efficiency. Single phase (120 V) window air conditioners and refrigerators will exacerbate this problem. Correcting this problem is as simple as rearranging circuit breakers in the service panels of a building. This measurement should be taken on a hot summer day when a building's mechanical systems will be operating at their maximum duty cycle. By balancing the loads across different phases, especially the mechanical loads, circuit heating can be reduced.

4.3 <u>Data Analysis</u>

Figure 19 is a graph of twenty-four days of usage (July 29 to August 22) measured at the secondary of the transformer that served the eighty apartments. The magenta line is KW, the yellow line is KVA and the blue area is KVAR. The initial correction was installed in the complex on August 7. Additional correction was installed on August 11 through August 18. You will note that the KVA and the KW start to overlap, indicating a power factor approaching 1.0. Figure 20 shows the power factor for the same period (blue) and the harmonic distortion (yellow and magenta). Before the correction was installed, the power factor varied between 0.86 and 0.93. During times of peak load when the PLIP's® were operating, the power factor varied from 0.985 to 0.995. As the load dropped and the PLIP's® correction was no longer needed, the power factor dropped to approximately 0.97 to 0.975. Note that the amount of KVAR present at the transformer after correction with a 122 KVA load (August 11), is less than the amount of KVAR present before correction with a 65 KVA peak load. That day was one of very few days during the summer of 2009 to exceed 90 degrees. Also note that the harmonic levels before and after correction are the same. The harmonic spikes were occurring prior to our adding correction and are not related to our equipment. Those seem to repeat on an approximately three week interval and last for three days. We are not aware of the source of those harmonics.

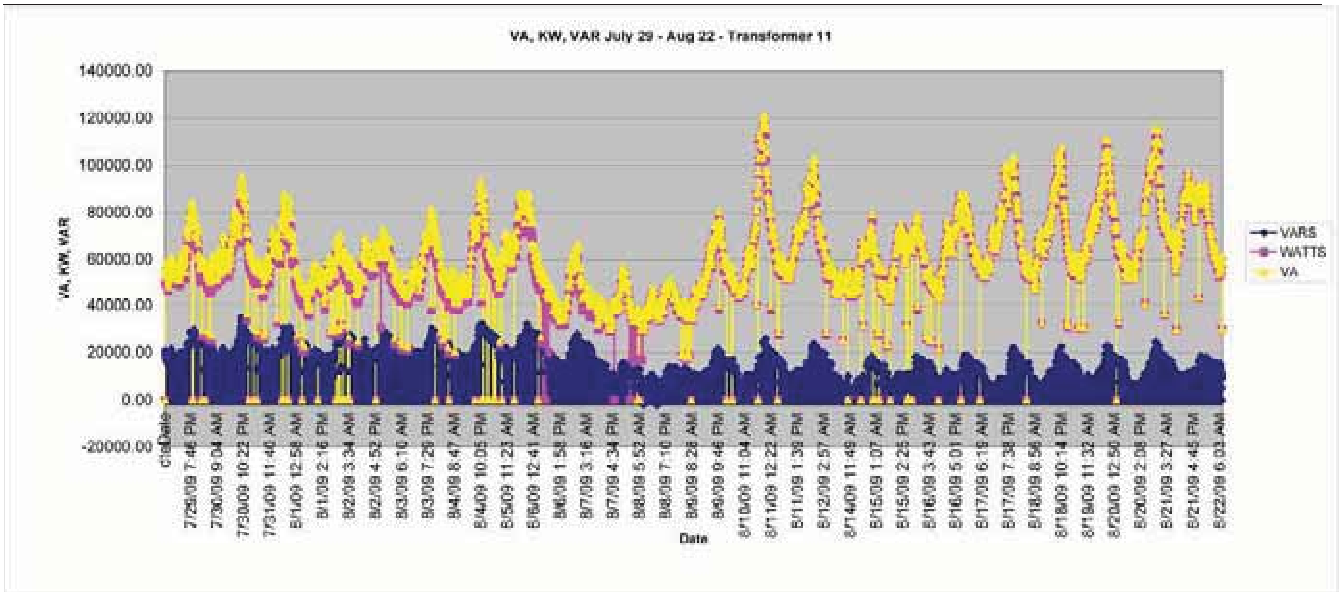


Figure 19: Transformer 11- Hilltop Terrace - Vars, Watts, VA July 29, 2009 – August 22, 2009

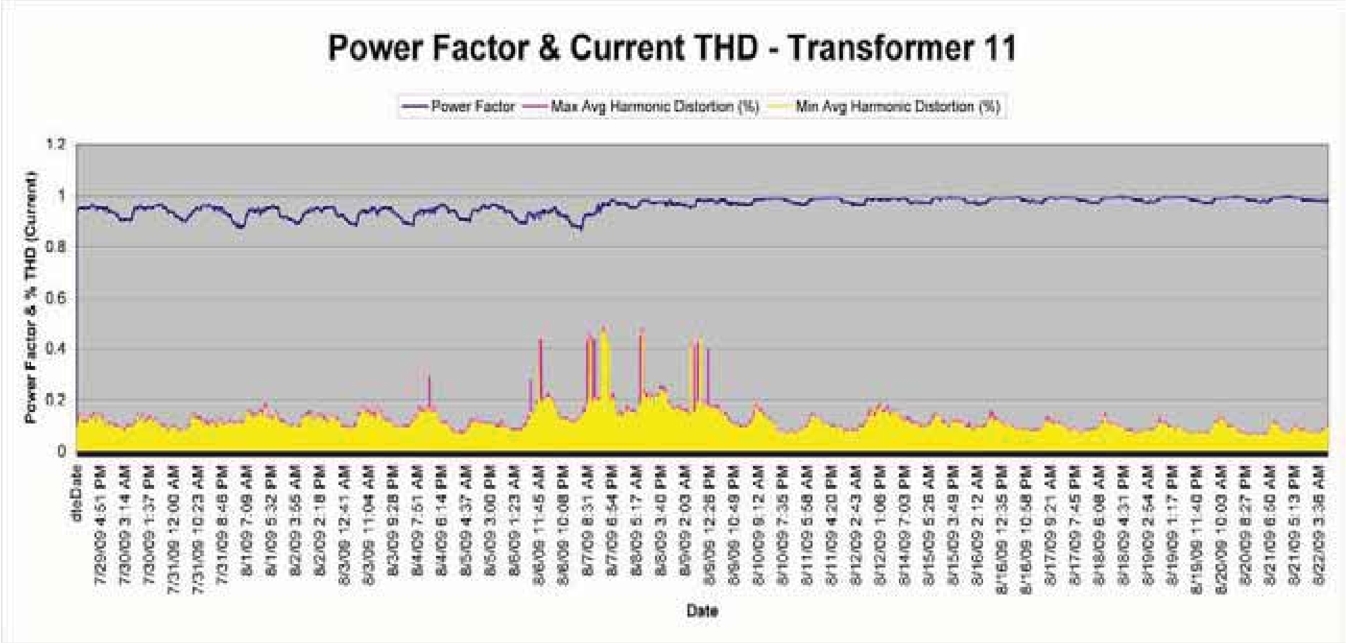


Figure 20: Transformer 11- Hilltop Terrace Power Factor and Harmonics
July 29, 2009 – August 22, 2009

The summer of 2009 was the second coolest on record in the New York area, making the execution of this project more difficult. Kilowatt output from the solar array that we are using for our solar reference is down 10% in 2009 versus 2008. Figure 21 is a graph of the transformer temperature (magenta), the monitor interior case temperature (dark blue), the monitor exterior temperature (yellow), and the solar output (light blue) for the same time period. The thermocouple that measured the transformer temperature was mounted to the surface of the unit. As the transformer had a much higher mass than the power monitor, its temperature varies much more slowly. Any rapid decreases in transformer temperature are the result of rainfall. During rainstorms, the measured temperature would drop below the transformer temperature and then rise back up to the ambient transformer temperature as soon as the storm passed. The difference in the transformer temperature from the monitor internal temperature is a function of thermal losses in the transformer resulting from inefficiencies and load. The power monitor, having a constant load and a much lower mass, more closely tracks the outdoor temperature plus the effects of solar loading. The power draw of each monitor is approximately seven watts. four watts of that is for the battery charger. The light blue shows the solar array output over time. The array is located within a half mile of the apartment complex. A fine blue line indicates no cloud cover. Where the light blue area is dense, it is indicative of solar fluctuations caused by clouds passing overhead.

It can be seen that the transformer temperature and the monitor temperature are greatly affected by solar loading. There were several days where the shell of the transformer was between 130 degrees-F and 140 degrees-F. A temperature rise on the exterior of the transformer will reduce its ability to dissipate heat, resulting in a temperature increase on the interior of the unit. As mentioned earlier, that will result in a decrease in efficiency.

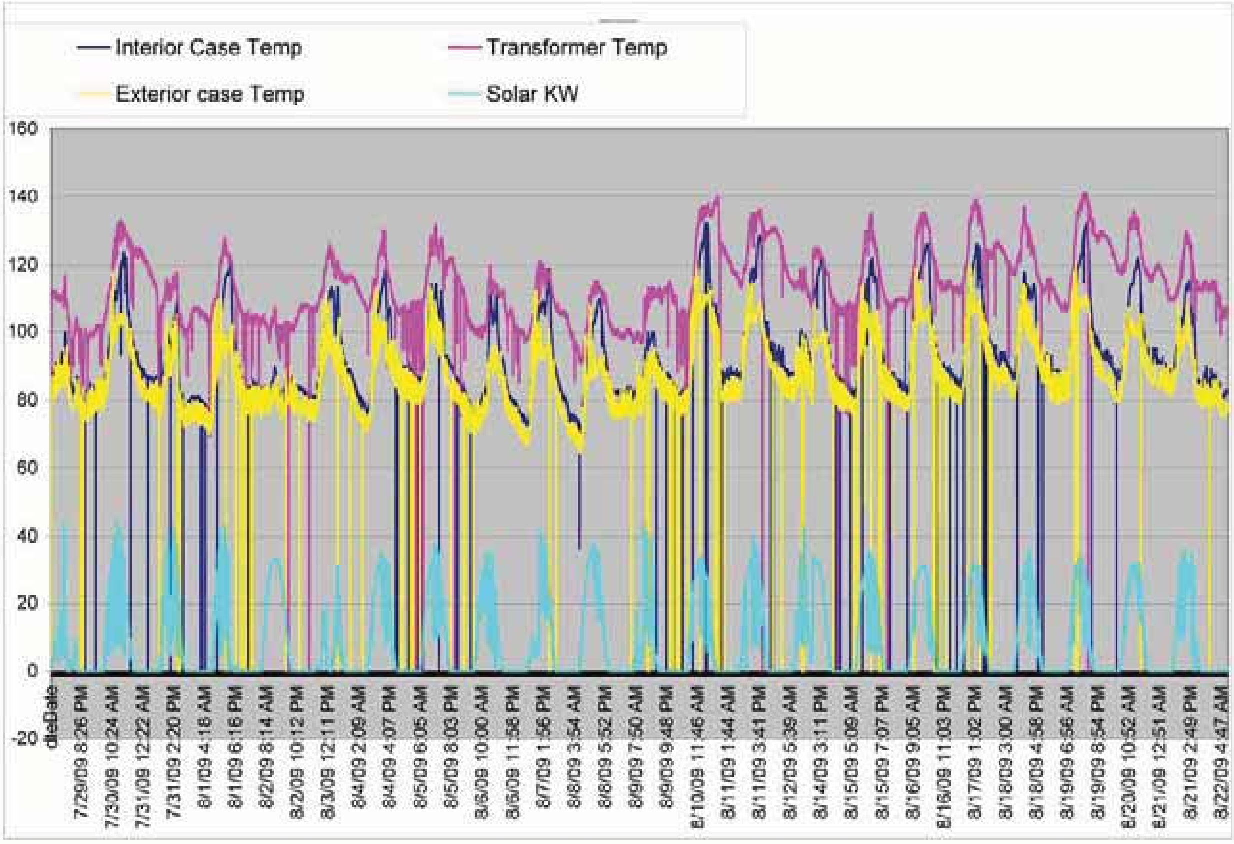


Figure 21: Transformer 11- Hilltop Terrace Temperatures July 29, 2009 – August 22, 2009
Temperatures in degrees-F, Solar output is in KW (light blue)

It can be seen from the figures above that we were able to reduce the peak load of the complex by approximately 6% when measured at the secondary of the transformer, resulting in a 12% reduction in related line losses from the point of correction back to the substation. The off peak load was reduced by approximately 9%. The period of increased load usually lasted approximately seven hours, starting at 4:30 PM to 5:00 PM, and continued until 11:30 PM to 12:00 midnight. The peak usually occurred between 8:30 PM and 9:30 PM, presumably as people turned on their bedroom air conditioners to cool the room before going to sleep. The minimum load usually occurred between 7:00 AM and 9:30 AM, approximately eleven hours after the peak. In the early morning, buildings will be their coolest from a lack of solar loading overnight, resulting in a lower cooling load. Also, residents will be turning off appliances at that time as they go to work.

To achieve this improvement in power factor required analyzing the base line reactive load of the facility during the cooler months. Correction was added at the buildings service entrance to correct the smaller reactive loads that are present. While this will not reduce losses after the meters, it will reduce line losses caused by the smaller loads in the 80 units from the service entrance back to the substation. Furthermore, it will work all year. A time delay relay with an "on delay" was added to the correction to ensure that it would not be active instantaneously after a blackout. The time delay is adjustable. It increases the cost of the device but as stated earlier, it is important to reduce the restart impedance in the event of a blackout. In addition, we installed 20 KVAR of correction using the PLIP's®. Based on measurements taken in June when it was still very cool outside, the peak load with no cooling for the transformer shown is approximately 40 KVA. That rises to between 80 KVA and 125 KVA on hot days during the summer. The PLIP's® were only installed on air conditioning units that were used frequently. Beyond a certain point, there is a diminishing return from adding more correction. All of the installed PLIP's® will not be operational simultaneously, as they only turn on when the associated air conditioner's compressor engages. They will not turn on if only the fan is operational. The PLIP's® achieved an energy savings before and after the meter. Based on measurements taken at individual units, we developed estimates of the savings. Figure 9 shows the waveforms for a 200 volt air conditioner, before and after correction. On that particular unit, a 15.5% current reduction was achieved, resulting in a line loss reduction of 27% related to that air conditioner. A 10% reduction in current was more common, with most improvements in the 7% to 12% range. 1 KVAR PLIP's® were used to correct the 220 volt units and ½ KVAR PLIP's® were used to correct the 120 volt air conditioners. The newer 220 volt air conditioners, when encountered, were left uncorrected. The energy savings calculations and the cost analysis appear in section 6.0.

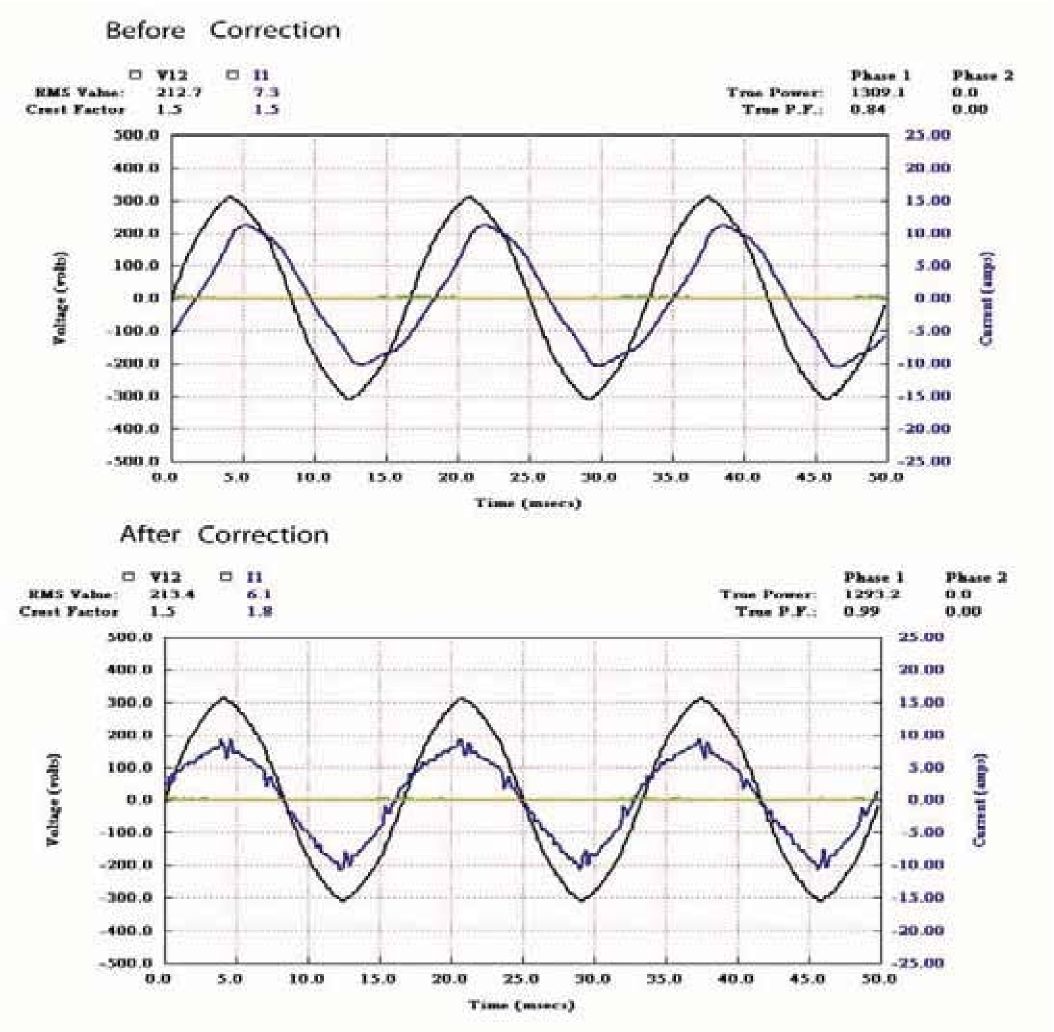


Figure 22: 220 volt window air conditioning unit before and after correction. Power Factor raised from 0.84 to 0.99. Current reduced from 7.3 amps to 6.1 amps, a 15.5% improvement.

4.4 Cost Benefit Analysis

Based on the techniques applied, and the increasing of the power factor at the complex, it is apparent that we achieved a reduction in losses. For the purposes of the analysis, we divided the day into two parts based on the power factor graph in Figure 20. There is the 14 hours where we achieved a power factor near unity and the 10 hour period where the power factor was near 0.97. In the calculations in Figure 23, at the end of the report, the 14 hour period is referred to as the "Peak Load" because it includes the peak period.

All calculations are based on average values measured before and after the correction was installed. The loss percentages are taken from Con Ed's values in Figure 1 and Figure 2. Based on measurements taken on equipment and the number of units that we installed, we estimate that the savings after the meter from this process will amount to approximately 0.5% (0.005) of load. This is far lower than many published estimates of associated savings related to power factor correction, but we wanted to be conservative in our estimates. Based on our experience at Hilltop Terrace, the complex will use 3090 KWH less annually and reduce the peak load by 0.6 KW for an installation cost of approximately $4,000. The return on investment (ROI) based on wholesale electricity costs and offset generation is approximately 9.3 years. As the effect of power factor correction on KW production is very predictable, the generation offset can be included. At present, new generation in the New York City area costs approximately $2,000 per KW to build. That does not include the cost of the additional transmission and distribution to transfer that power. As we have no accurate way to calculate the cost of that, we did not include it in our analysis but it will reduce the 9.3 year ROI. We also did not include the savings from reduced system maintenance if this were applied over an extended area. That would also contribute to reducing the 9.3 year ROI. As these devices have a lifespan of over 20 years, they will far outlive the period for the ROI. Much of the existing equipment that these devices would be installed to correct could easily be in service for another ten years to twenty years, well beyond the period of the ROI.

To put the cost of this process into perspective, a cost comparison can be made between the cost of power factor correction and the cost of photovoltaic solar, a technology that the government has deemed worthy of public subsidies. While solar "generates" KW and power factor reduces KW, both technologies will have the same net effect on fossil fuel generation. A power meter located at the utility substation would not be able to determine if the 3090-KWH annual decrease in usage was due to the power factor correction system that we installed or a 2800 watt residential solar array at the same location (Annual KWH ≈ Array Capacity x 1.1) . At the present day cost of $7.50 per watt for installed photovoltaic solar, the 2800 watt array would cost $21,000. The power factor system that we installed would cost approximately $4,000 for the 80 units, based on mass production costs of the devices. The net cost, when the value of offset generation is deducted, is $2,800. If we add a 20% cost overrun to the total and figure that the power factor correction system would have a net cost of $3,600, it would still cost 83% less than a solar array with the equivalent KW output. The public subsidy on that array would be approximately $8,000, or over double the cost of the power factor system if it were 100% subsidized.

This is an important point because even though both systems would offset the same amount of KWH, the power factor system would have a much less visible effect on the utility customer's monthly usage bill. Where the savings would appear would be in the distribution portion of the bill in the form of reduced losses. The lack of an easily visible savings would make it difficult to induce the customer to install the system. That would mean that a large public subsidy would be needed to get these systems installed.

We are not trying to imply that photovoltaic solar is not worthy of public funding. What we are stating is that if solar is worthy of public funding, a technology that would cost less than half as much in public dollars to obtain the same net result is certainly worthwhile. In addition to the KWH reduction, power factor correction also provides a definite generation offset because the resulting energy savings are predictable and continuous, which solar does not provide. If public funding does not seem like a viable option, a one dollar monthly surcharge on each utility bill for five years would cover the entire cost. 80 apartments x $60 = $4,800. It is a minimal expense to achieve a large gain.

Furthermore, if it is worthwhile to spend money to fix the problem after installation, the equipment standards should be changed to address the problem before the equipment is installed. While the ROI is 9.3 years on a retrofit, we estimate that it would be less than three years if the power factor correction was installed at the factory. That figure is based on the cost of energy lost across the entire system, not just after the customer's utility meter.

4.5 Conclusions

Based on our measurements and results obtained at Hilltop Terrace, we have come to the following conclusions:

- The power factor is sufficiently low in the apartment/multi-family environment that improving it will result in a substantial energy savings throughout the entire utility system, when measured in KWH.

- We can cost effectively improve the power factor for existing apartment buildings in the near term.

- Standards need to be modified so that new apartment complexes are designed with a high power factor and a balanced load as part of the design criteria. Compliance should be verified prior to a Certificate of Occupancy being issued.

- Power Factor Correction in this environment does not significantly increase the amount of harmonics measured at the utility transformer.

- Power Factor Correction must be load based and must only operate when needed. Excess capacitance attached to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance would add extra impedance that would have to be energized, applying extra load to the system during a restart.

- Standards need to be modified so that new appliances are required to have a high power factor as part of the design criteria. This includes refrigeration and especially, air conditioners. Some of the newer 220 volt air conditioners operated with a power factor near 0.99. None of the 120 volt air conditioners encountered operated with a power factor above 0.92, including the newest units that were less than a year old. Most of the measurements were taken on hot days, so the units would have been operating as efficiently as possible.

- Standards need to be modified so that new appliances and other electrical devices to be attached to the utility have more strict limits on the amount of harmonics that they generate per watt of consumption. In particular, this will apply to computers, televisions, and fluorescent lighting. Harmonics adversely affect electrical efficiency. Furthermore, harmonic mitigation can be very costly to implement.

While the last two items on the list will increase the price of appliances and other electrical devices, the accrued savings on energy will more than offset the additional cost.

PART 5 – SINGLE FAMILY RESIDENTIAL

5.0 Background Information and Implementation

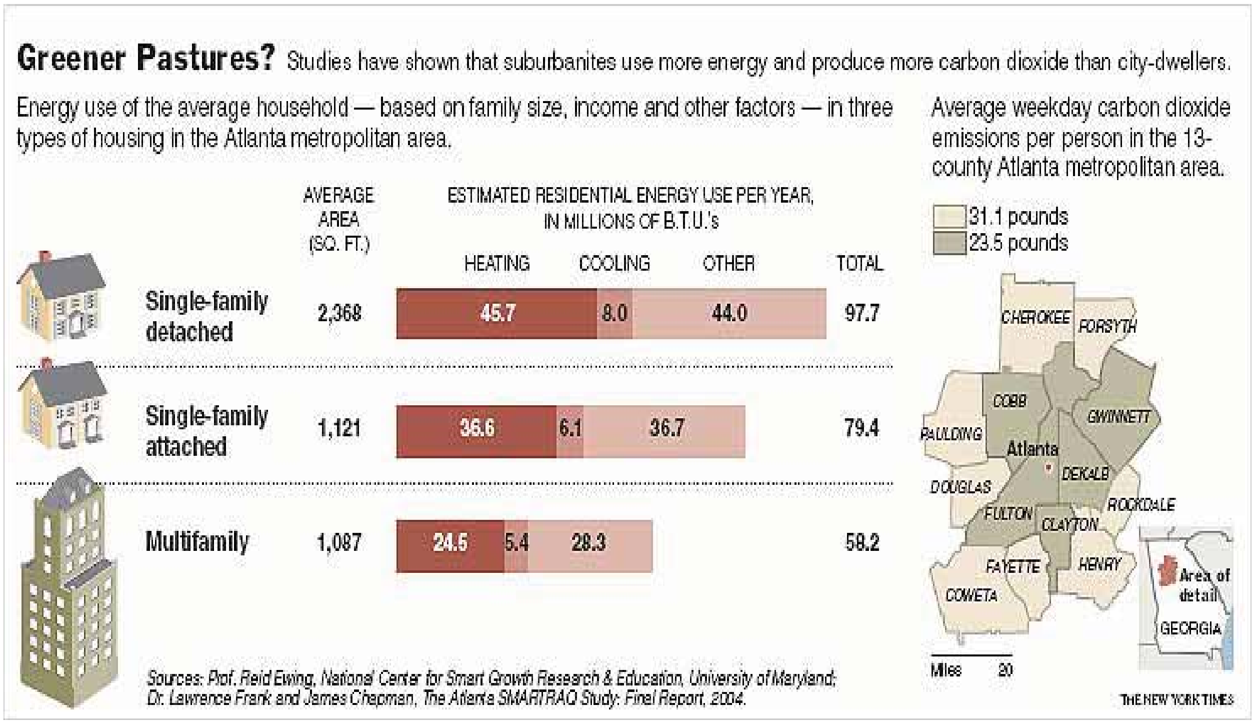
While the US Census states that 58 percent of residential units in the New York Metropolitan area are in buildings with four or more units, and 20 percent of residential units are in buildings with fifty or more units, there are still 20 percent of residential units that are in single family homes.[9] In the United States, as a whole, 64 percent of housing was in single family homes. In addition, in 1990, almost 40 percent of residential homes in the New York Area were built prior to 1939. That was second most in the nation. Only the Boston Metropolitan area had a higher percentage of old homes.

Single family homes present a slightly different problem than the multi-family residential units. As their loads are higher, there are fewer residential units attached to each transformer. In addition, many of the larger, individual motor loads are hard wired to the electrical service as opposed to being plugged in. This makes reactive correction more labor intensive and more expensive. Where we could walk to four different residential units at Hilltop Terrace within a minute, the distance between single family residences increases the time needed to perform any individual analysis or equipment installation, which will result in increased costs. Still, independent of the increased costs, there are significant issues with reactive load in the single family residences when these loads are aggregated on the system. In an article from the New York Times in February, 2008[10], the higher energy consumption of single family residential homes is discussed. Figure 23 documents the conclusions of the article. While they represent only 20 percent of all dwelling units in New York, based on our measurements and other literature, they account for approximately 40 percent of residential electrical consumption and about half of all residential reactive power discharge onto the system.

The neighborhood that was analyzed for this project consisted of 53 homes serviced by eight different transformers. Four transformers were single phase, 240 volt units and four were three phase, 208 volt units. Home sizes varied between approximately 2,500 square feet to 4,500 square feet. The neighborhood was initially built in the late 1950s to mid 1960s, but many of the homes have been enlarged since that time. Figure 24 is a map of the project area, showing the transformer locations.

[9] – SB/94-15, Issued July 1994, US Department of Commerce, Bureau of the Census

[10] – Don't Let the Green Grass Fool You, Alex Williams, NY Times February 19, 2008


Greener Pastures? Studies have shown that suburbanites use more energy and produce more carbon dioxide than city-dwellers.

Sources: Prof. Reid Ewing, National Center for Smart Growth Research & Education, University of Maryland; Dr. Lawrence Frank and James Chapman, The Atlanta SMARTRAQ Study: Final Report, 2004.

Figure 23 – Relative energy usage of various types of residential units – NY Times February 10, 2008

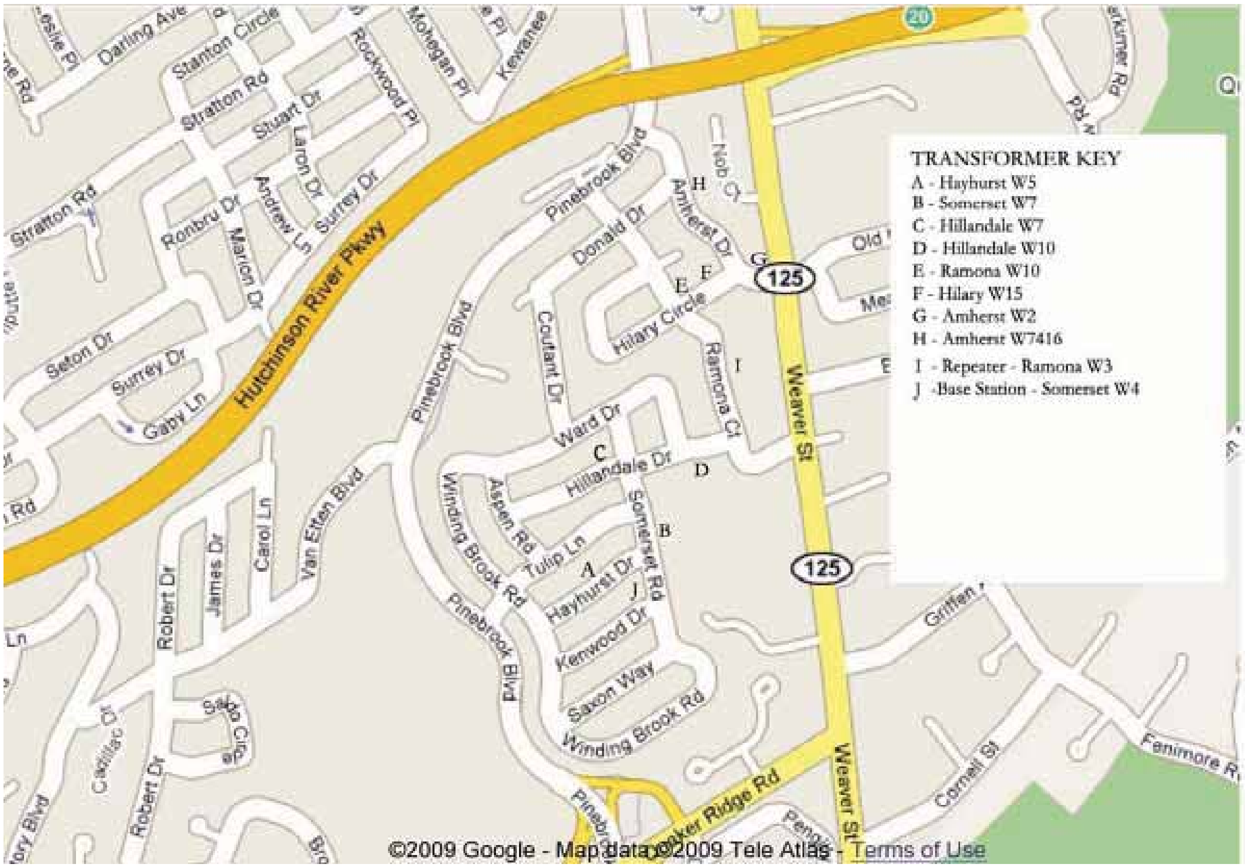


Figure 24 – Single Family Residence Project Area

For the analysis of the single family residential area, we installed a system that was very similar to that used at Hilltop Terrace for the multi-family analysis. As only four-to-seven homes are attached to each transformer, we installed eight monitors across a wide area with a central data collection point that transmitted the files back to our main server. The monitoring system was installed in mid-June, 2009 at the same time that the Hilltop monitors were installed.

The neighborhood has had significant, well publicized power problems over the years, which is why we chose that particular area. Even with an offer of a no-cost potential solution to help mitigate the problems, getting homeowners to allow us to perform reactive correction was very difficult. Letters were sent to all fifty three homeowners announcing two different evening meetings to explain the project. It was discussed at a New Rochelle City Council meeting broadcast on a local cable channel, and calls were made to every homeowner to encourage participation in the project. Despite that, only nine of 53 home owners attended the meetings and only 11 homeowners agreed to participate. With such a low percentage of homes to analyze, we decided to only monitor the power in the neighborhood and put off the correction until the summer of 2010, so that we could focus on the other phases of the project where we were meeting little to no resistance. We were going to attempt to persuade additional homeowners to participate during meetings in the spring of 2010.

The power monitors were designed, fabricated, and tested during a period of twelve weeks after confirmation of receiving project funding. They were tested to ensure functioning through a 48-hour blackout. The 12 week window was a function of when project funding was received and the utility’s time frame for installation of the devices where it wouldn’t interfere with their operations during the summer. Unfortunately, on March 13, 2010, Westchester County experienced the 100-year storm. Power was lost in the entire project neighborhood for approximately four-to-five days as a result of scores of downed trees and branches damaging power lines and utility poles. As a result, the monitoring system ceased functioning at that time.

By the time that the monitoring system had failed, we had collected nine months of data through the hottest and coldest months and had sufficient information to perform an analysis, based on the experience gained at Hilltop Terrace. The system can be resurrected without much difficulty, but it will require the utility providing a bucket truck and labor. After the storm, the utility, with the help of many crews from several other states, was preoccupied with restoring power to residents and repairing the massive damage done to the distribution system. A research project justifiably became a very low priority.

5.1 Results

Figure 25 shows the data collected during an 18 day period from July 24, 2009 through August 10, 2009 for one of the eight transformers in the project area. The data is similar for all eight transformers. The load graph (top) is also very similar to the one measured at Hilltop Terrace. Still, each single family dwelling uses approximately 3.8 times as much power, on average, and discharges approximately five times as much reactive power back onto the system. In the second graph in figure 25, the same 40 degree temperature swings can be seen on the transformer surface, indicating over an 8 percent increase in wire resistance and a corresponding loss in transformer efficiency. The third graph shows the power factor and the harmonic distortion. The power factor varied between 0.8 and 0.96, but the vast majority of the time it averaged approximately 0.91. It can be seen that the harmonic distortion is significantly higher than in the same graph shown for the multi-family residential units. The bottom graph in Figure 25 shows the harmonics normalized for load. A lower load with an equivalent amount of distortion will result in a higher percentage THD (Total Harmonic Distortion). This graph shows the actual amount of distortion present over time.

The single family homes generate far more harmonics than the multi-family dwellings. This contributes to the lower power factor. The sources of the harmonics can be compact fluorescent bulbs or other fluorescent lighting, plasma TVs, computer power supplies, and video game power supplies, among others. Unfortunately, even reducing the harmonics does not reduce power consumption. Harmonic filters will reduce the level of harmonics present on the system, however they convert the harmonics to heat, which is still lost energy.

Where we could use an inexpensive device that had a minimal installation cost to correct the air conditioners and other reactive loads in the multi-family dwellings, the central air conditioners and many other reactive loads in the single family homes are hard wired. Any correction that would be added would need to be installed by an electrician and would need a follow up electrical inspection that would make the correction cost prohibitive. A correction system could be installed at the service entrance, which would reduce the reactive load on the utility's distribution system, however that would be far less effective as there would be no reduction of losses within the customer premises. A small capacitive correction system located at the service entrance would also reduce harmonics as the capacitors will absorb harmonics prior to their being transmitted to the utility's distribution system. Such

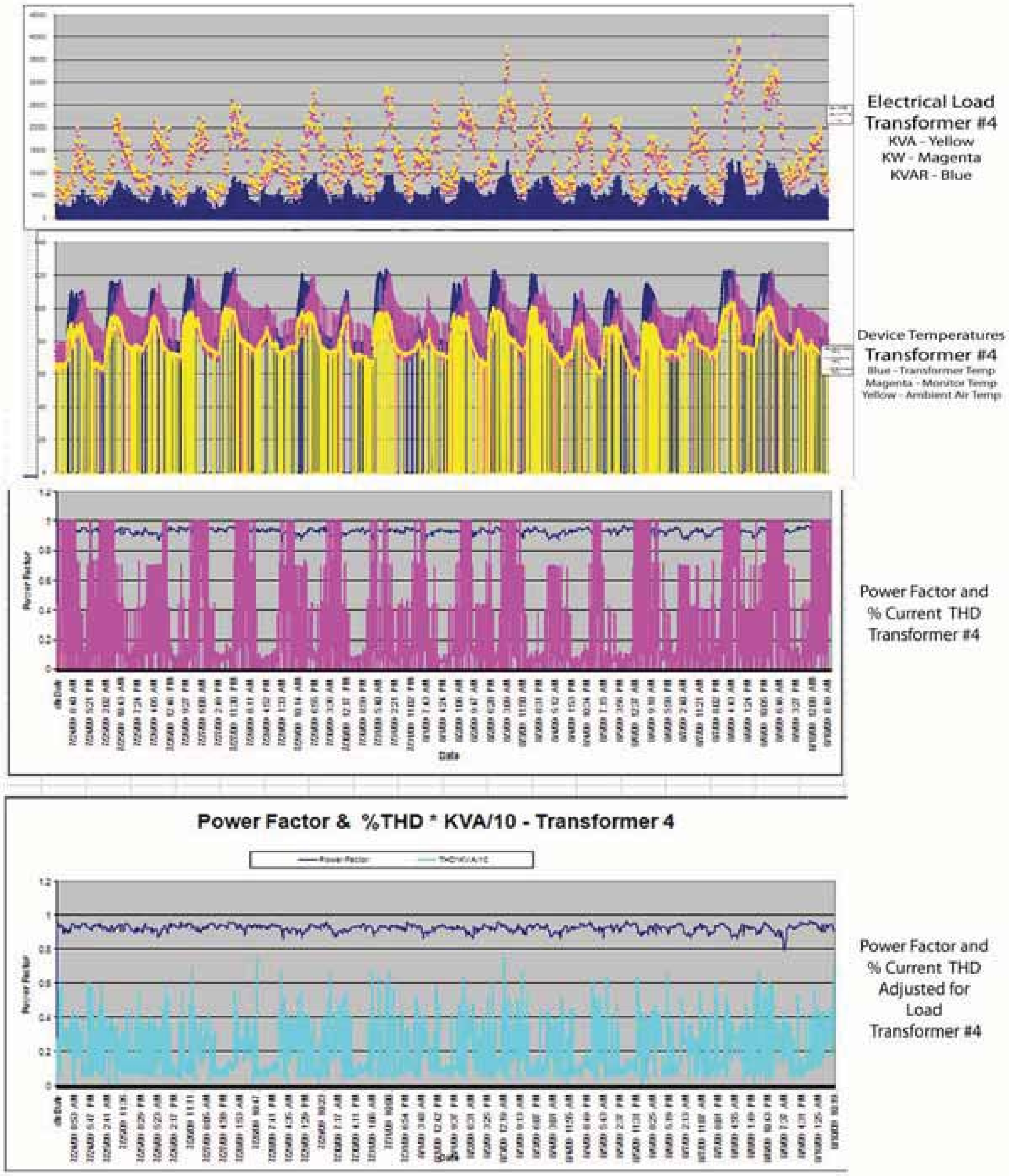


Figure 25 - Typical Transformer Data from the project area

a system was tested in Whitby, Ontario during a trial experiment during 2005[11]. While harmonics were not addressed by that project, the conclusions and recommendations of that report on the Whitby Pilot Project were as follows.

> "The results of the pilot indicated that the addition of capacitance at the residential home reduces the demand requirements at the transformer. Further assumptions indicate that installation of the units on mass will reduce the generation requirements throughout the province."
>
> "We recommend that the findings of this pilot be shared with government officials as a viable means to help address the supply and transmission issues within the province."

As demonstrated with the vending machines, multi-family residential, industrial, and commercial locations, the capacitive correction will definitely reduce demand requirements at the utility's transformer. The issue becomes the system cost and the resulting benefit. In larger facilities with a large reactive load, it is cost effective to employ electricians to install the necessary equipment needed to mitigate the problem. The saved energy will pay for the cost of the system in a short period of time. In a single family residence, the reactive load is not sufficiently large to justify the labor needed to correct it. This is unfortunate because the reactive power being discharged by those residences, when aggregated, is sufficiently large to cause significant losses on the system. The only way to cost effectively address the reactive power problem in this domain is to have the correction built in at the factory. While this will increase the initial equipment cost, the savings to the customer will pay for the increased cost within a few years.

---

11 - Power Factor Correction at the Residential Level – Pilot Project, Whitby Hydro Energy Services Corp., September 12, 2005

5.2 Other issues encountered in the single family residential environment that affect energy Efficiency

5.2.1 Larger Single Family Homes

Single family homes have a reactive load that is disproportionately larger than a dwelling in a multi family building. Nevertheless, as single family homes get larger, their reactive load becomes even more disproportionate. This is because many of the large single family homes have additional loads that have a lower power factor. Those loads that seem to be omnipresent in larger single family homes include pool pumps, automation systems, and additional refrigeration. Figure 26 is the waveform from the service entrance of an 10,000 square foot home in Scarsdale. This measurement was taken at 11:50 AM when no one was home and very few lights were on. The load was nearly 14 kilowatts with a power factor of 0.88. During the measuring period, the load varied between 13-KW and 18.5-KW. The home

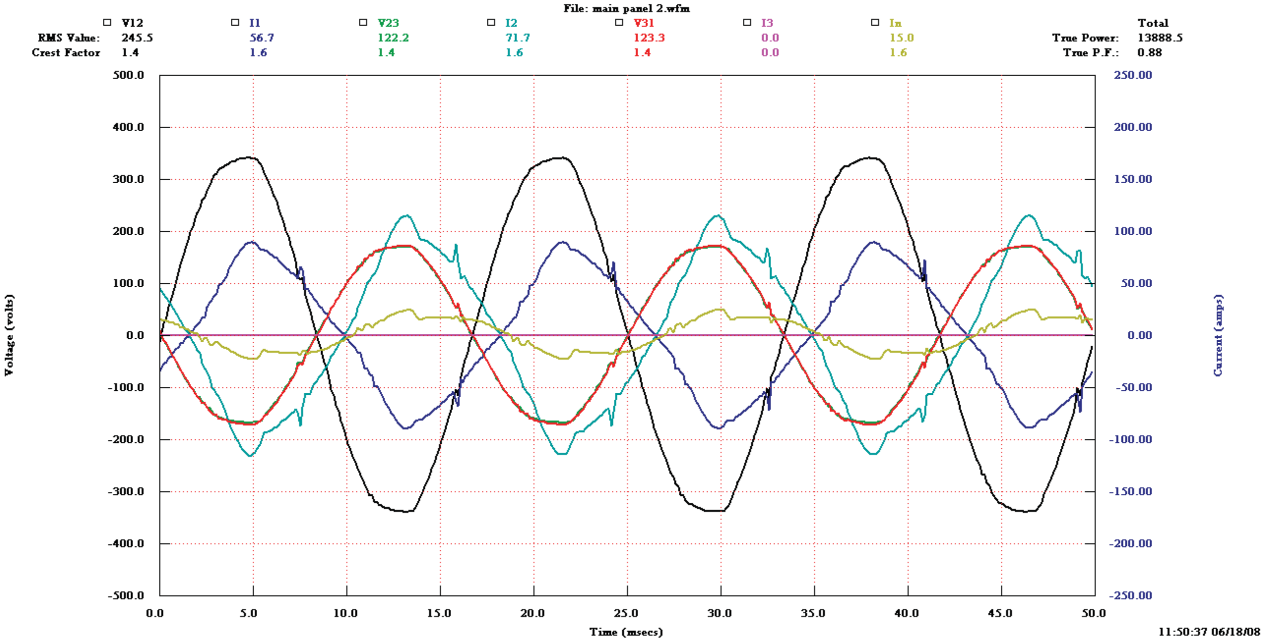


Figure 26 – Service entrance waveform of an 10,000 square foot home in Scarsdale, NY.

included a large automation system, a swimming pool, external sump pumps used to lower the water table, and multiple televisions with the associated accessories (DVD's, amplifiers, etc.). With the smaller homes and the multi-family dwellings, the power factor would tend to rise as the load rose. In this larger home, the power factor was relatively constant between 0.88 and 0.90, despite a 42% variation in KW load during the measuring period.

5.2.2 Load Balancing Between Phases

An issue that was encountered during monitoring at some of the locations was a phase imbalance at the secondaries of the transformers. This occurs because the dwellings that are serviced by the transformer are not wired so that the larger loads are properly distributed across the incoming circuits. In a three phase service, the dwelling loads are distributed across three incoming phases, while most of the lighting will be between a phase and the neutral. If circuit breakers are not properly positioned in the service panels, there will be a higher load on some phases and a lower load on others. On hotter days when the load rises due to increased cooling demands, the increased loads on portions of the utility transformer will decrease the efficiency. If the loads are properly balanced, the transformer and the related circuits will operate at cooler temperatures and their efficiencies will increase. Many residential loads use a single phase at either 120 or 208/240 volts. This makes it more difficult to balance the loads when the incoming service is three phase. While it is difficult to balance the single phase loads within a single dwelling, it is more difficult to balance the loads at the transformer where multiple single phase loads merge. Many of these homes were built at different times and there was no specification as to circuits on which to place larger loads. The phase imbalances are less prevalent with many industrial or commercial three phase services because many of the larger loads are three phase motors that tend to naturally balance the load between the phases.

This will also occur on the single phase 240 volt transformers if too many 120 volt loads are wired to one of the 240 volt legs and fewer are wired to the other. The phase balancing issue was expressed anecdotally by the utility linemen that installed our monitors. During discussions, they mentioned that when they were reconnecting wires after a distribution line was downed, certain wires attached to a transformer arced far more than others when they were reconnected. The larger arcs are indicative of a higher load. Figure 27 shows the relative loads on several transformers from which we collected data. The I^2R losses on the circuits attached to Transformer 6 will be approximately five percent higher on a hot day than they would be if the load was balanced as it is on Transformer 8. The higher loads will raise conductor temperatures on the more heavily loaded part of the circuit and increase their resistance, in addition to the higher currents present. On transformer 7, the imbalance is more apparent at lower loads,

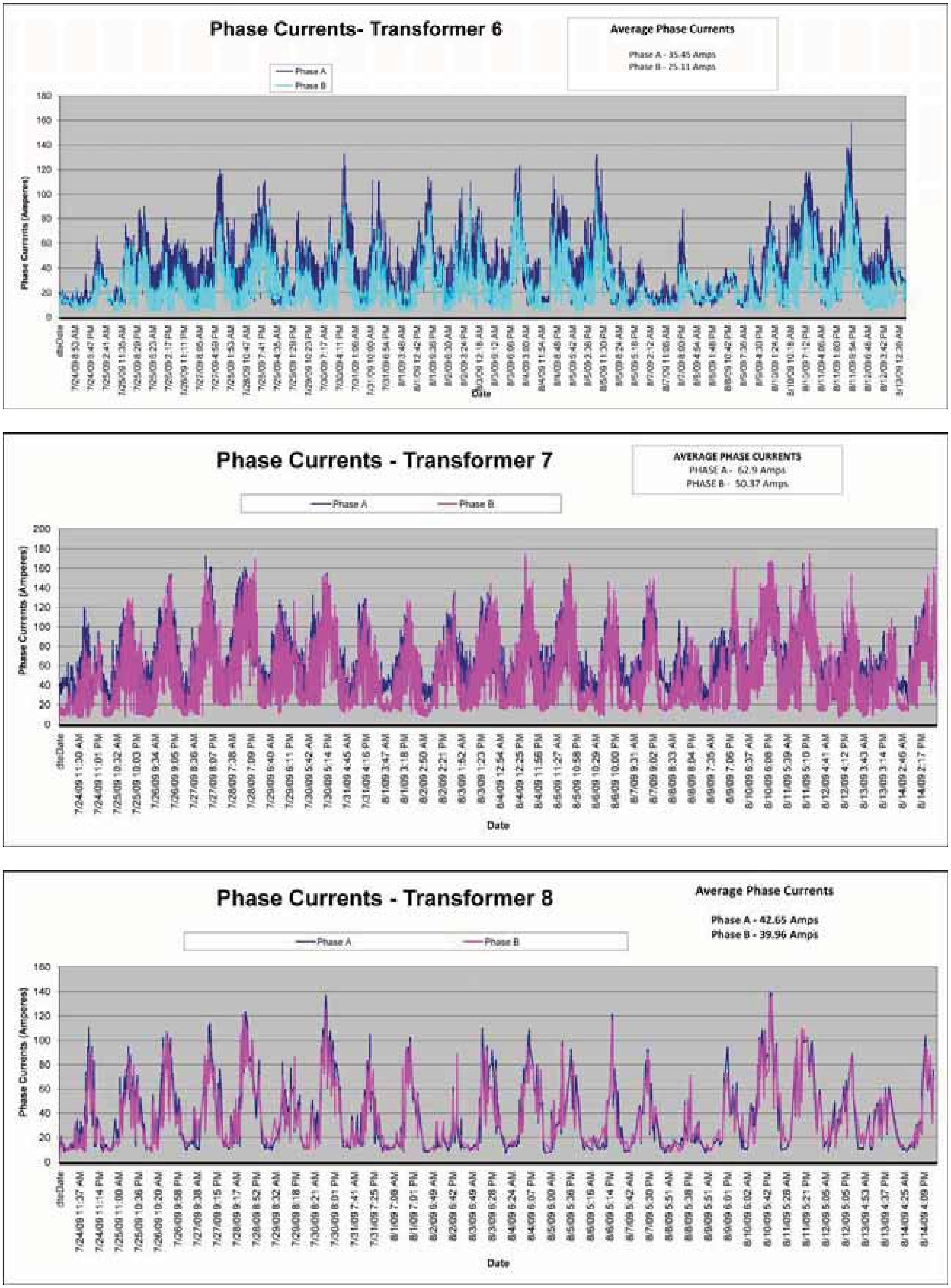


Figure 27 – Current Loads – Single Phase, 240 volt Transformers. Circuits with imbalances similar to that attached to Transformer 6 can operate with an efficiency almost five percent lower than the circuit attached to transformer 8.

while at higher loads, the circuits are more in balance. On transformer 6, the loads become more imbalanced as the load increases. That results in the lowest efficiency when the circuits are most heavily loaded. This loss of efficiency is in addition to the inefficiencies caused by a lower than optimal power factor.

Figure 28 shows phase balances on some of the three phase transformers that we collected data from. It can be seen that one phase on all three transformers is carrying substantially less load than the other two phases. The situation is most apparent on number 5 where phase A is more than 60% less loaded than the other two.

5.2.3 Charlatans Selling Power Factor Correction

One issue that we have encountered over the past eighteen months are the effects of the “Charlatans” that sell devices that will connect at the service entrance and claim to reduce the customer's utility bill by 20% to 40%. These are simply service entrance power factor devices that will not save anything for the utility customer. They will help to improve the power factor on the utility system. However, they are an “Always On” type of device, they will add impedance to the system if there is a restart after a blackout. In addition, if they are sized larger than the reactive load of the building that they are installed in, they could actually increase the customer’s utility bill. If the devices are oversized, they will absorb VARS from neighboring services and increase the currents in the building in which they are located. The quantity of wire that is between the device and the meter will determine the amount of extra thermal (I^2R) loss that will occur, and for which that the customer will have to pay.

Unfortunately, these Snake Oil salesmen have given the process a bad name. Power Factor Correction has merit, but only if done properly. With most utilities in the United States only billing for kilowatts (KW) and not kilovolt-amps (KVA), the only place that power factor correction will save the utility customer money by reducing load, is to physically install the correction at the load.

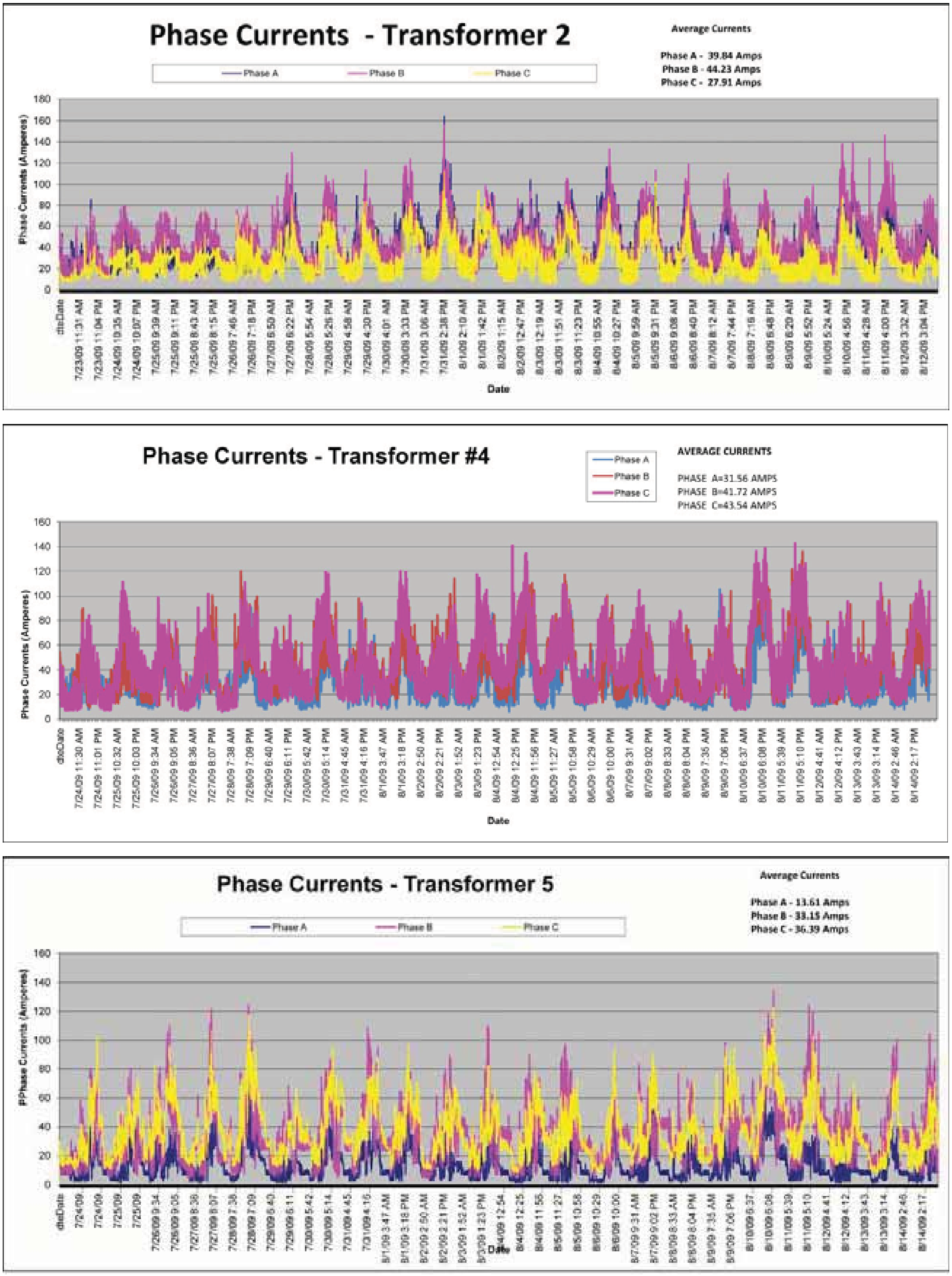


Figure 28 – Current Loads – Three Phase Transformers

5.3 Conclusions

Based on our measurements in a neighborhood of single family homes, we have come to the following conclusions:

- The per unit load on the utility is substantially higher for single family residences than for multifamily dwellings. The reactive power load, including harmonic discharge, is disproportionately higher for the single family residences.

- The power factor is sufficiently low in the single family home environment that improving it will result in a substantial energy saving throughout the entire utility system, when measured in KWH.

- We **cannot** cost effectively improve the power factor for existing single family homes in the near term using aftermarket devices.

- Standards need to be modified so that new single family homes are designed with a high power factor and a balanced load as part of the design criteria. Communication must be improved between utilities and electrical contractors to ensure that all of the distribution circuits are evenly loaded. Compliance with power factor requirements and balanced load requirements should be verified prior to a Certificate of Occupancy being issued.

- Power Factor Correction in this environment would not significantly increase the amount of harmonics measured at the utility transformer, any more than it did in the multi-family setting.

- Power Factor Correction must be load based and must only operate when needed. Excess capacitance attached to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance would add extra impedance that would have to be energized, applying extra load to the system during a restart.

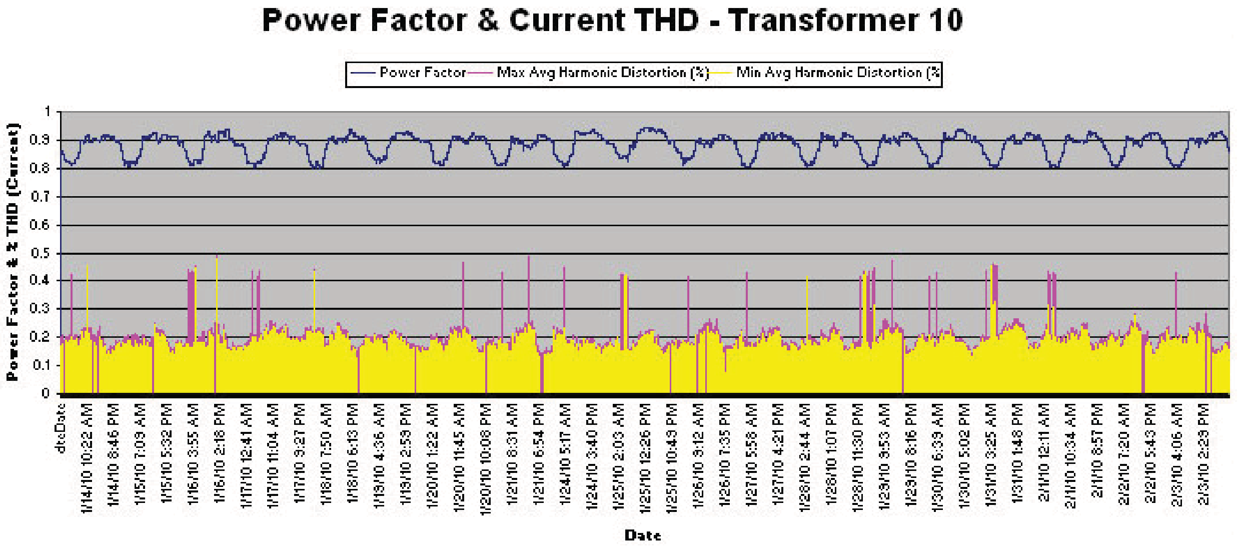
- Standards need to be modified so that new appliances are required to have a high power factor as part of the design criteria. This is extremely critical in this environment as it is exceedingly expensive to correct after the equipment is installed.

- Standards need to be modified so that new appliances and other electrical devices to be attached to the utility have more strict limits on the amount of harmonics that they generate per watt of consumption. In particular, this will apply to computers, televisions, and fluorescent lighting. Harmonics adversely affect electrical efficiency. Furthermore, harmonic mitigation can be very costly to implement. Harmonics are more of an issue, relative to load, in the single family home than in all of the other types of buildings that we measured. As a result, harmonic mitigation will greatly help power quality and reduce losses in single family homes.

While the last two items on the list will increase the price of appliances and other electrical devices, the accrued savings on energy will more than offset the additional cost.

6 Harmonic Analysis

During the course of the project, several engineers from the utility companies, based on their experience with sub-station capacitors, and engineers that have worked with service entrance correction, have been adamant in their opinion that adding capacitance to correct power factor will greatly increase harmonics on the utility system. To date, we have not seen that significant an increase in harmonics resulting from the “At Load” correction systems that we have installed. An example of this is shown in Figures 29 and 30. Figure 29 shows the power factor and current distortion at the secondaries of two transformers, labeled Transformer 10 and Transformer 11 for the same time frame, January 14, 2010 through February 3, 2010. Both transformers share the same 4160 volt primary, and are physically located approximately 200 yards apart, 300 yards via the wires. Transformer 10



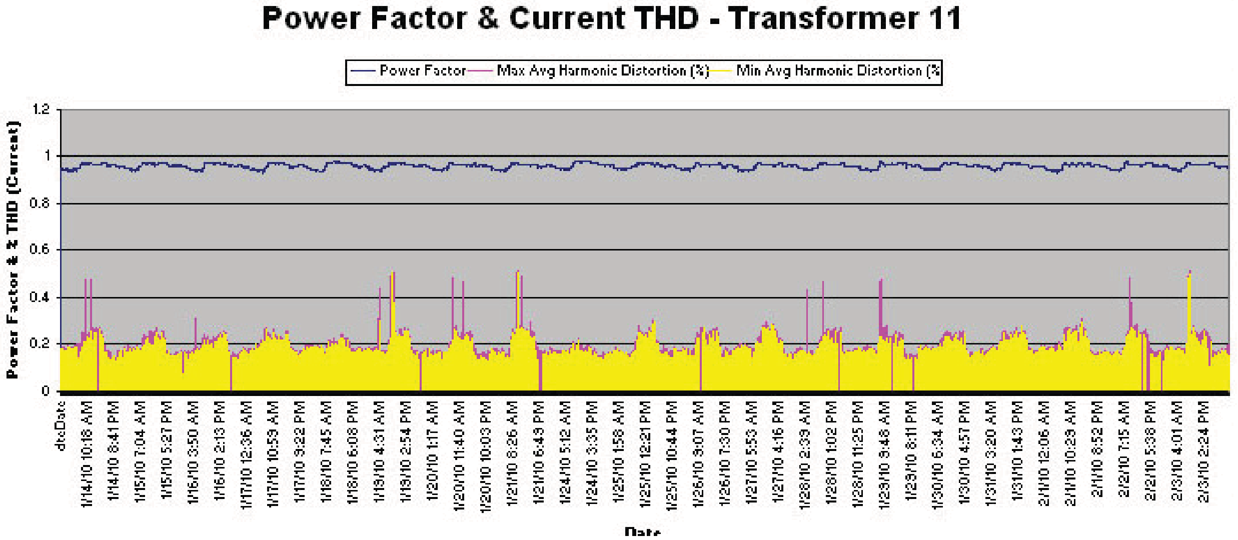


Figure 29 – Power Factor of Two Transformers that share a primary. The apartments attached to transformer 11 have had the power factor raised. Nothing has been done to the apartments attached to transformer 10

serves approximately 70 apartments where the reactive power has not been corrected. Transformer 11 serves 80 apartments where the reactive power has been corrected. Both apartment groups date to the mid-1960s and have apartments of similar size. As a result, they have similar types of loads that will transmit similar levels of harmonics onto the system. The power factor at the secondary of transformer 10 varies between 0.81 and 0.92. The power factor at the secondary of transformer 11 varies between 0.95 and 0.97. The average current distortion at transformer 11, the corrected system, is no higher than at transformer 10, the uncorrected system. Figure 30 shows the voltage distortion at the secondaries of the two transformers during the same twenty-one day time period. It can be seen that the two graphs move in unison, indicating that

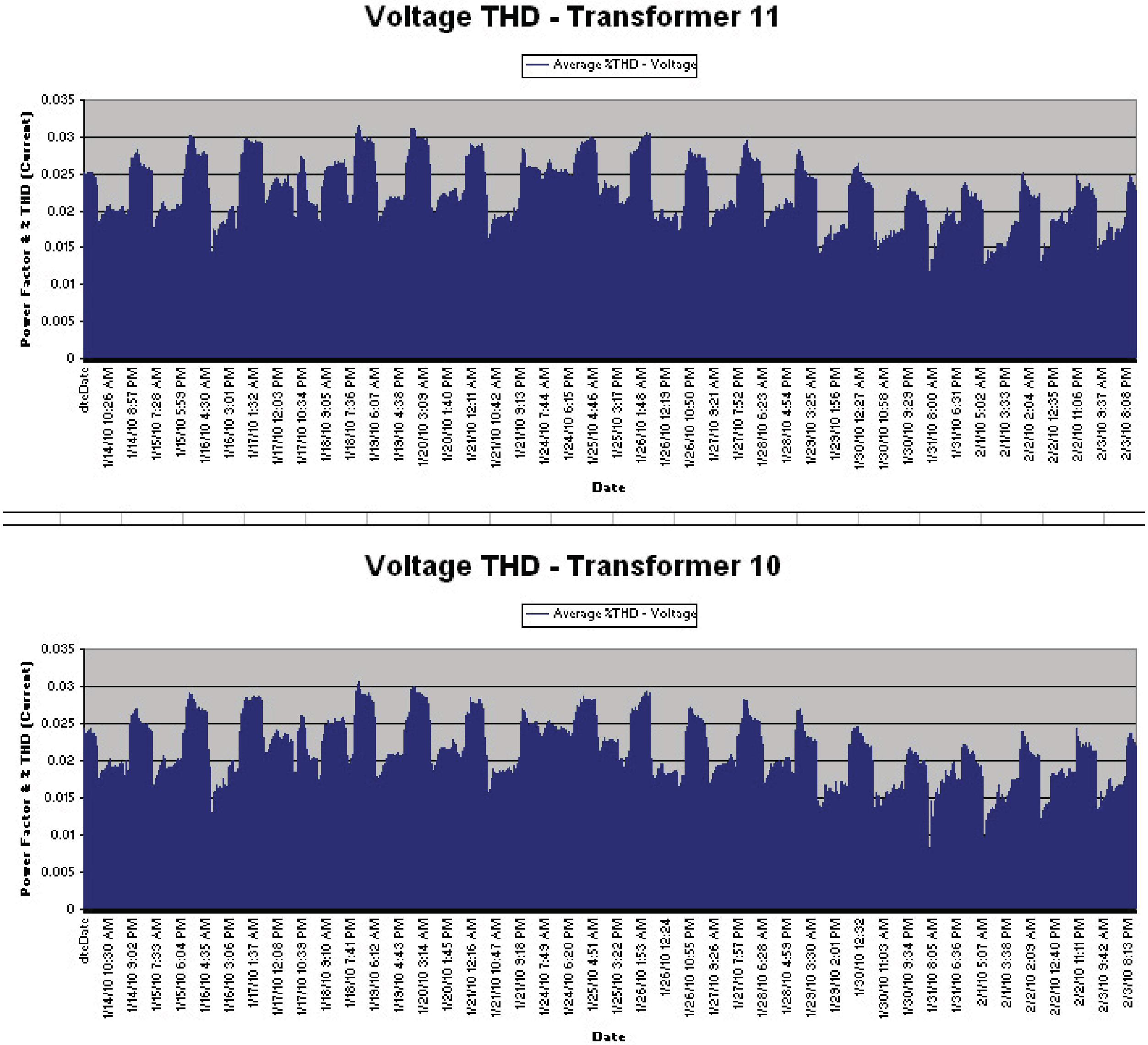


Figure 30 – Voltage Distortion at the secondaries of two transformers that share a primary. The apartments attached to transformer 11 have had the power factor raised. Nothing has been done to the apartments attached to transformer 10.

the vast majority of the distortion is coming from the primary. The voltage distortion at the secondary of the corrected transformer is higher by 0.1% at almost every point, which is miniscule by any standards.

From this data, and similar data that we have collected elsewhere, the conclusion that we have drawn is that the larger, concentrated capacitance present in the substation correction systems and the service entrance systems will generate higher magnitude harmonics on the larger conductors at those locations, which also have a lower resistance. The smaller, distributed capacitors used in the "At Load" correction create much lower levels of harmonics. Those are then dissipated on the smaller conductors, with higher resistances, prior to reaching the service entrance, or transformer secondaries, where we were measuring harmonic levels. At those lower levels, the wires act as a harmonic attenuator.

To test this hypothesis, we created an experiment. To implement the experiment, we needed a harmonic source. From our earlier experiments with Compact Fluorescent Light Bulbs (CFLs), we knew that they would generate significant levels of harmonics. We used twenty 13 watt CFLs on a single phase circuit. The test apparatus is shown in Figure 31. The test apparatus will hold 60 bulbs, twenty per phase, across three phases. We used a single phase of the board for our test.

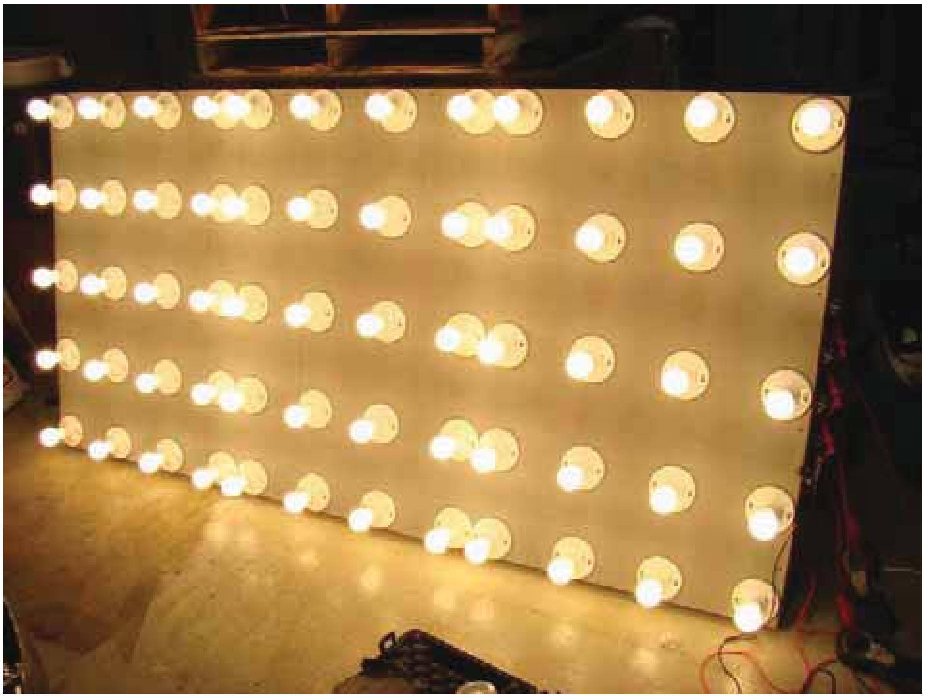


Figure 31 – Light Board used to generate harmonics

We then measured the harmonics at increments of 50 feet from the harmonic source by adding 50 foot or 100 foot, 12 gauge extension cords between the board and the metering point. These wire lengths will simulate the wiring between the correction, where the harmonics are generated, and the service entrance of the facilities where we measured the net effect of the correction. Averages of five measurements at each distance were used to eliminate spurious data, although all measurements obtained at each distance were very similar. The experiment was repeated using 16 gauge extension cords. Figure 32 below shows the harmonic levels at the contacts to the light board (0 feet). Please note the Voltage %THD of 4.05% and the K-Factor of 18.41. As a comparison, the K-Factor with a linear load of incandescent bulbs in the board was 1.46 while the Voltage %THD (%VTHD)was under 3%.

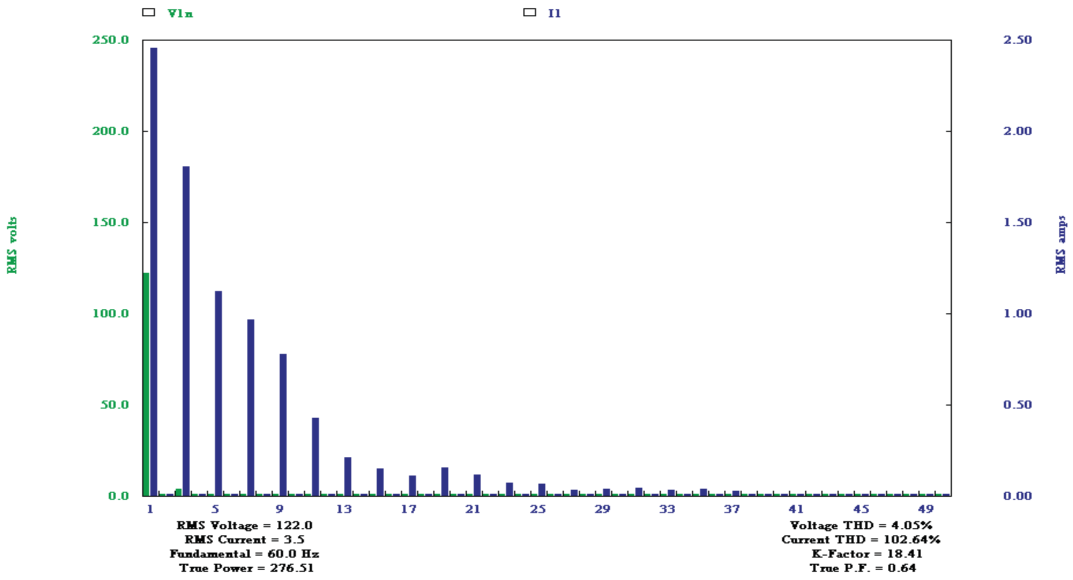
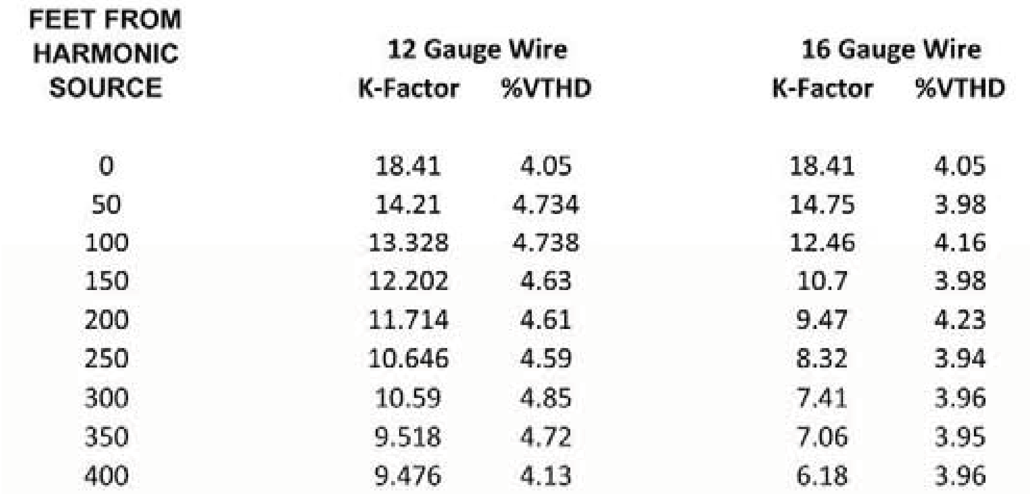


Figure 32 – Harmonic Levels at the contacts of the light board.

The K-factor is a number derived from a numerical calculation based on the summation of harmonic currents generated by the non-linear load. The higher the K-factor is, the more significant the harmonic current content. The algorithm used to compute K-factor is:

$$\frac{\sum_{1}^{50} (i_h * h)^2}{\sum_{1}^{50} i_h^{2}}$$

Where h is the harmonic number. Details of the calculation method can be found in IEEE Standard 1100-1992. A K-Factor of 1.0 indicates a linear load with no harmonics. Higher K-Factors are indicative of higher levels of harmonics. Figure 33, below, shows the values of K-Factor for each increment of wire length from the harmonic source. It can be clearly seen that the harmonics decrease with increasing distance from the harmonic source. A graph of the values appears in Figure 34.



FEET FROM HARMONIC SOURCE	12 Gauge Wire		16 Gauge Wire	
	K-Factor	%VTHD	K-Factor	%VTHD
0	18.41	4.05	18.41	4.05
50	14.21	4.734	14.75	3.98
100	13.328	4.738	12.46	4.16
150	12.202	4.63	10.7	3.98
200	11.714	4.61	9.47	4.23
250	10.646	4.59	8.32	3.94
300	10.59	4.85	7.41	3.96
350	9.518	4.72	7.06	3.95
400	9.476	4.13	6.18	3.96

Figure 33- K-Factor vs. Distance from Harmonic Source

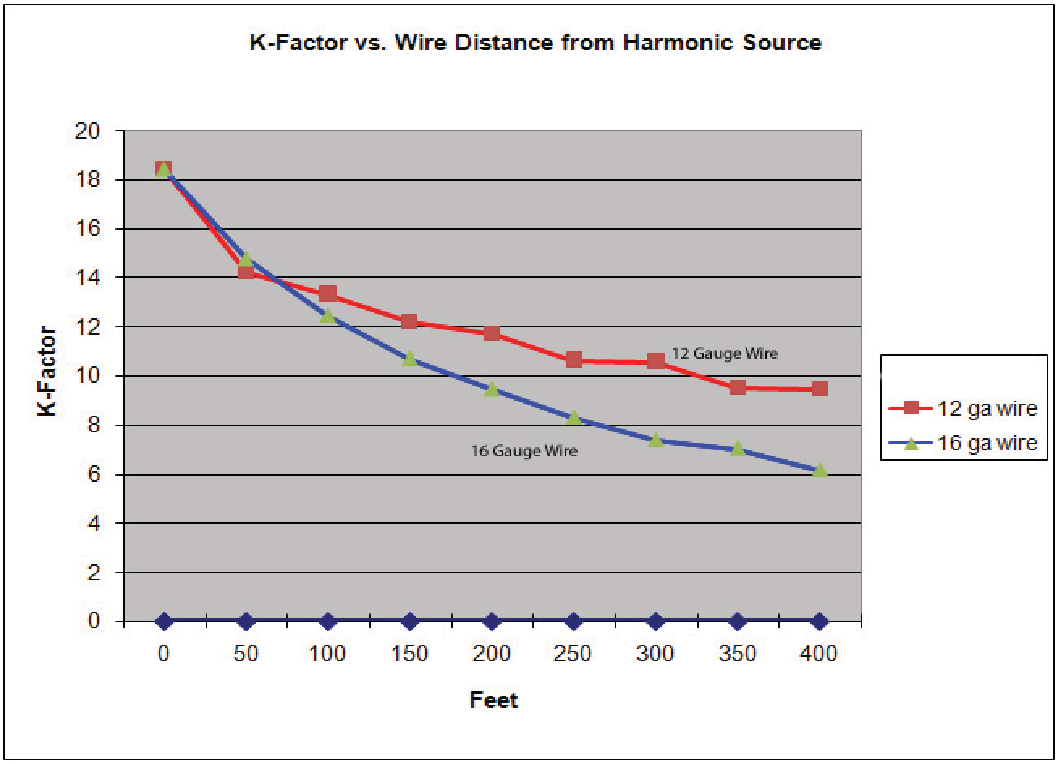
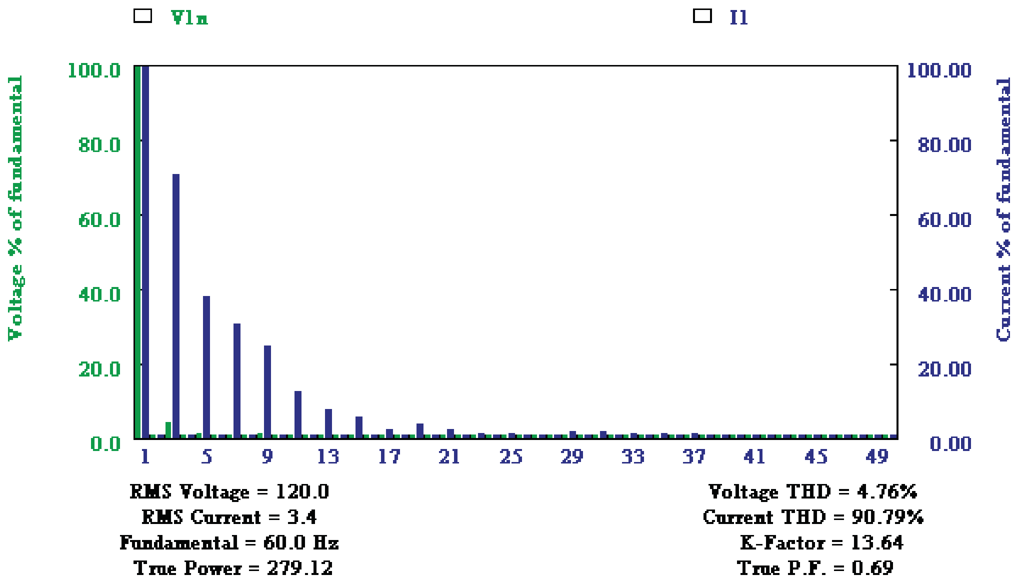


Figure 34 K-Factor versus distance from the harmonic source .

Figure 35 shows the harmonic level after passing through 100 feet of 12 gauge wire. The K=factor has dropped by 27%, primarily as a result of the attenuation of the harmonics above the 5th order, although the data indicates that there was some attenuation of the third harmonic.

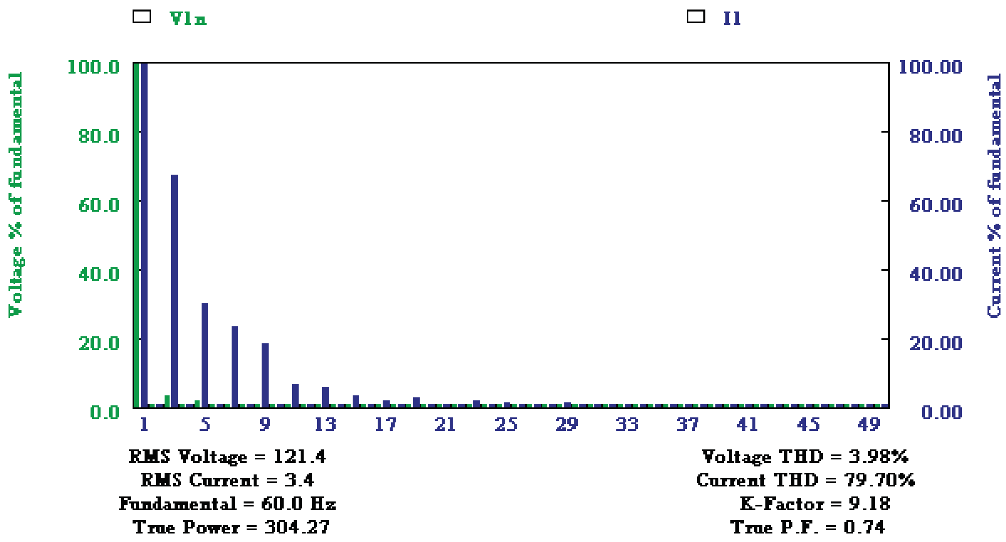
Figure 36, below, shows the harmonic level after passing through 400 feet of 12 gauge wire. From the results of the experiment, it is apparent that the harmonics dissipate very rapidly, especially the higher order harmonics. Over the first 50 feet of wire, 23% of the harmonics dissipated, however, harmonics of different frequencies attenuate over different distances. Harmonics from the 5th and above are greatly reduced at 400 feet, while there is still a presence of the third harmonic. The %V-THD rising and falling over the 400 feet is likely related to the various frequencies dissipating at the different distances and increasing the %V-THD.



RMS Voltage = 120.0
RMS Current = 3.4
Fundamental = 60.0 Hz
True Power = 279.12

Voltage THD = 4.76%
Current THD = 90.79%
K-Factor = 13.64
True P.F. = 0.69

Figure 35 – Harmonic Levels after passing through 100 feet of 12 ga wire



RMS Voltage = 121.4
RMS Current = 3.4
Fundamental = 60.0 Hz
True Power = 304.27

Voltage THD = 3.98%
Current THD = 79.70%
K-Factor = 9.18
True P.F. = 0.74

Figure 36 – Harmonic Levels after passing through 400 feet of 12 gauge wire

From the power data, it is also clear that the harmonics are dissipating as thermal losses. In figure 32, at “0” feet, the True Power consumed by the bulbs is 277 watts. After 400 feet, the True Power has risen to 304 watts, an increase of 27 watts, or 10%. I^2R losses for 400 feet of 12 gauge wire (.00187 ohms/foot) at 3.5 amps would be 9 watts. The balance of the 27 watt increase, 18 watts, is a result of the harmonics dissipating as heat within the wires.

The graph in figure 34 also shows that the harmonics attenuate more rapidly in the smaller, 16 gauge, conductors. This is to be expected as the wire resistance is greater in the smaller conductors.

It is important to remember that the initial harmonic levels at “0 feet” were much higher than those created by the smaller capacitors used for the “At Load” correction. We used higher levels of harmonics for the experiment to be more easily able to measure the rate of attenuation of the different harmonics. As we have seen from our on-site measurements, the smaller harmonics generated by the smaller capacitors have nearly vanished by the time that they have reached the service entrance of the facilities where we have worked.

We are not trying to imply that a wire is a suitable means of removing harmonics in other applications. Nevertheless, with the low levels of harmonics that we are measuring while installing the smaller “At Load” capacitors, the vast majority have attenuated before reaching the service entrance of the facilities being corrected.

This is the likely explanation as to why we are not measuring the levels of harmonic distortion that many engineers are expecting. The impedance of the wires is acting as a harmonic attenuator to remove the low levels of harmonics being generated by the distributed capacitance. It is indicative of another advantage of performing the correction at the load, as opposed to installing larger amounts of capacitance at the service entrance of a customer premise or at the utility sub-station.

On a separate note, related to power factor and energy consumption, this experiment also clearly documents that CFLs result in more consumption within the customer premises than advertised on the package label. Each 13 watt CFL (60 watt incandescent equivalent) will actually consume approximately 22 watts of generation capacity on the entire system, after all of the harmonics have dissipated as heat. Utilities should be aware of this when planning their efficiency programs based on CFL lighting.

7.0 “At Load” Reactive Power Correction vs. “Service Entrance” Reactive Power Correction

The pros and cons of correcting power factor are dependent on the types of loads found within each facility. For a building that has large harmonic generating loads, such as a server farm, or one that needed power with extremely low levels of harmonic distortion, such as a hospital, a system located near the service entrance that employed harmonic mitigation might be preferable. Still, most facilities that we have seen do not need this type of “ultra-clean” power, have primarily displacement power factors resulting from motors, and also have lower levels of harmonics. In these cases, “At Load” correction has two major advantages over the service entrance systems. They are:

- **Shorter return on investment.** Even though the initial cost of the At Load system will be higher than the cost of the Service Entrance system, the savings are greater. The service entrance system will only save the customer on Var charges, while the “At Load” system will reduce both demand and usage charges by approximately two percent every month. In addition, the decreased usage after the meter, obtained with the “At Load” system, also decreases the generation requirements of the utility. In the longer term, if widely adopted, these reduced costs will eventually be reflected in customer bills. The reduced operating costs also lead to a shorter return on investment. The additional installation and equipment costs of larger ”At Load” systems (>150 Kvar) will be recovered within the first six to eight months. With smaller services, where service entrance systems would not be cost effective because of the high cost, “At Load” systems will still generate savings to offset the investment within a relatively short time period.

- **Fewer harmonics.** As demonstrated in Section 6, there are fewer harmonics created with the distributed capacitance of the “At Load” systems than with the larger, concentrated capacitance of the service entrance systems. This also reduces costs, both by generating fewer harmonics that might damage equipment, and by lessening or eliminating the need for expensive harmonic mitigation systems.

8.0 Economic Analysis Comparing "At Load" Correction Costs for Various Sized Services

During the past two years, we have measured and corrected (reduced) reactive power loads in several types of locations (environments) with several different service sizes. The economics for all services, similar to the sizes that we measured, will not be identical. Based on the fact that the collected data and the resulting economics follow an expected, intuitive pattern, it is very likely that the facilities documented here are fairly representative of what is attached to the utility system.

Figure 37 is a bar graph showing the economics of reactive power correction in the four different types of environments that we have chosen for the project. Figures 38 and 39 are the data tables used to create the bar graph. The four environments are Industrial, Commercial, Residential, and a fourth that is a subset of the commercial environment, refrigerated vending machines, and commercial refrigerators. The last category was added during the course of the project when it was realized how much reactive load for which these machines account. The economics of aftermarket correction are documented (shades of blue), in comparison to the costs if the correction was mandated by the government to be installed in the equipment (shades of green) when it was manufactured. Subsidies for power factor correction, on the light blue bars, are calculated to equal the savings on generation and substation correction that would result from having the correction installed. Depreciation is not included in the cost analysis because it is not a "tangible" value. It is an accounting value that is used to reduce taxes owed. It would only be applicable to commercial entities. In addition, the costs of reactive power correction are also compared to the costs of installing photo-voltaic solar arrays (PV). As documented in earlier papers, I am not against PV Solar. It serves a valuable purpose and will eventually provide a great deal of energy at a low cost. Still, it is a widely accepted "green" technology that is heavily subsidized by the government through rebates and tax credits. As such, it is logical to compare the economics of one technology that reduces utility load at the customer premise (Power Factor Correction) to another technology that does the same thing (PV Solar).

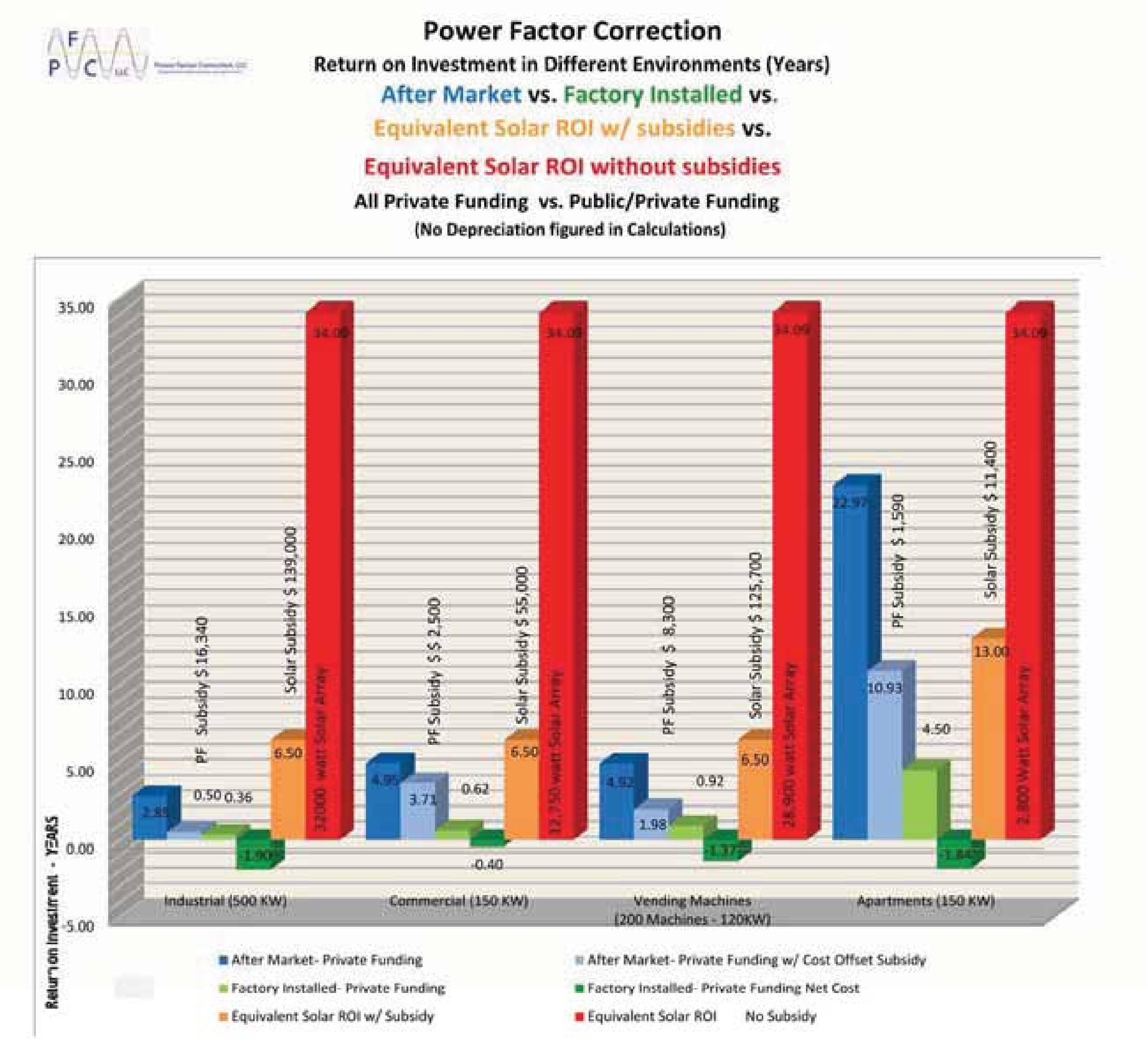
From the graph, it can be seen that After Market Power Factor correction, without subsidies, costs far less than PV solar in all four environments. With subsidies, it becomes very cost effective in all but the residential domain, however the return on investment there is still less than solar. In addition, the subsidies that would be required to make reactive power correction extremely cost effective are far smaller than those currently in place for PV solar. Localized wind turbines are currently more expensive than PV.

The dark blue bars show the return on investment if the customer pays for the entire process. With depreciation included, the ROI of the Industrial and Commercial correction would be reduced by 25 percent to 33 percent. As vending machines are typically installed in commercial locations, the ROI of these installations would be similarly reduced. If the customer is subject to reactive power charges from the utility, the ROI will be even further reduced.

Reactive power correction also has the advantage that it is not weather dependent or shading dependent, and occupies far less space. As a result, it can be installed everywhere for a much lower cost. As it is not weather dependent, it will also provide a generation offset. The utility can be assured that it will reduce load at times of peak load during the day, without concern for the amount of cloud cover or obstruction shading. That allows the costs of generation to be used to offset the costs of correction. Also, correction added at the customer level eliminates the need for correction at the substation, providing an additional cost offset. The existing correction can then be applied to further raising the Power Factor on the transmission system on days of peak load. As reactive power correction is far less controversial than choosing a site for generation, it can also be implemented far more quickly than a power plant. In the amount of time that it would take to obtain permits and build a generating plant, the reactive power correction will already have paid for itself.

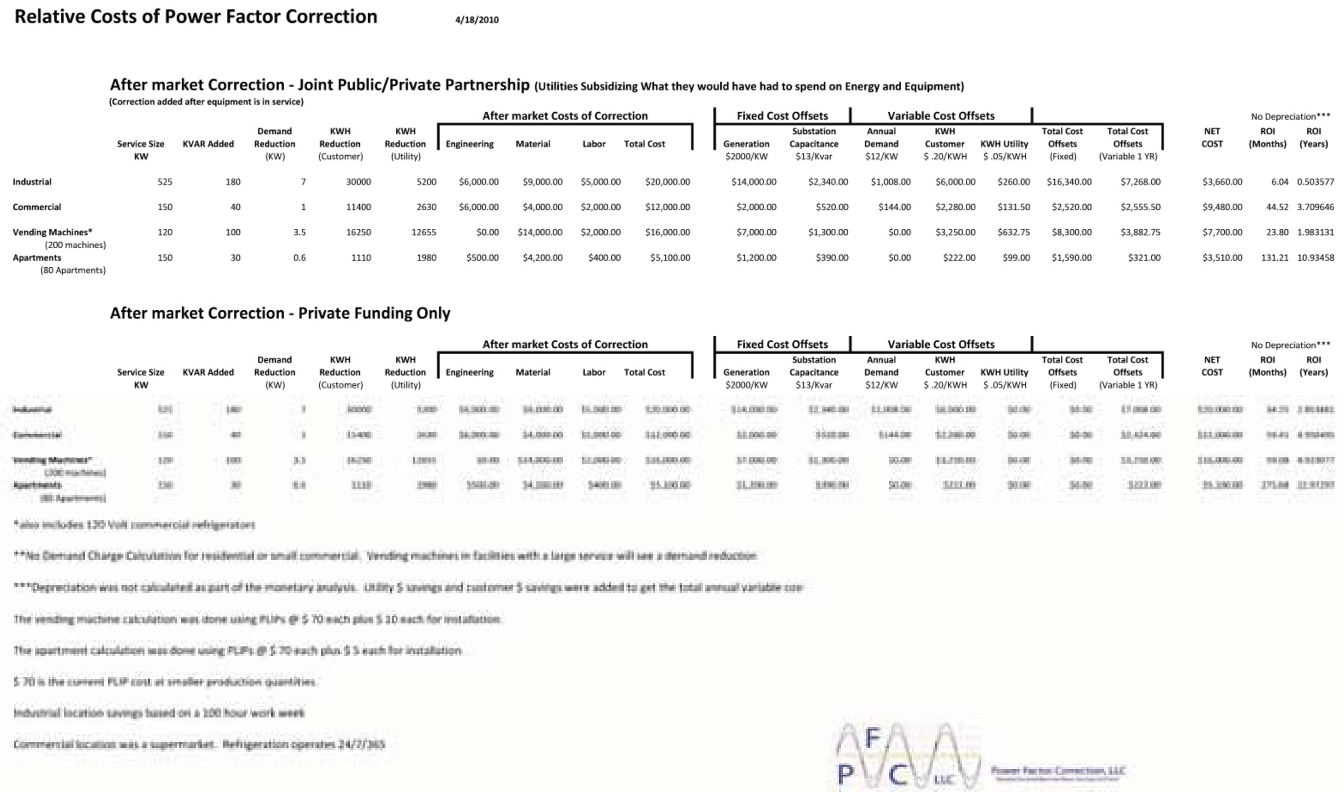
The apparent dissipation of harmonics that results from correction at the load also reduces the cost of adding harmonic mitigation to the system. That was not figured into the economic analysis. In addition, reactive power charges (KVAR Charges) were not calculated as part of the ROI. They would not affect all service sizes, and where KVAR charges are present, they vary by area and utility. For example, a 300Kvar facility with a peak demand of over 500-KW per month would save approximately $450 every month in reactive power charges under a recently enacted Con Ed tariff

In addition, every Kilowatt-Hour generated results in two pounds of CO_2 emissions. For the industrial facility with a twenty hour day and a 7-KW reduction, that yields 280 pounds per day, or approximately 67,000 pounds annually (33.5 tons). For the supermarket, with 24 hour operation of its refrigeration, a 1.25-KW reduction results in an 11 ton annual CO_2 reduction. The economics of greenhouse gas reduction have not been considered as the models are subject to interpretation. Although, there is certainly no negative effect to the large reductions of carbon emissions and other pollutants that would result from implementing this process.



The chart above shows the relative returns on investment (ROI) of Reactive Power (Power Factor) correction in the several environments that have been measured for this project. The dark blue bars show the ROI for the four environents when the customer pays for after market devices to be installed. The light blue bars show the ROI with the utility subsidizing an equivalent amount to what they will have to spend on generation and substation capacitance if the correction is not implemented. The amount of the subsidy is listed above the light blue bar. The light green bars document the return on investment to the utility customer for the extra cost of their equipment if the equipment manufacturer installs the reactive power correction. The dark green bars document the net cost of factory installed correction to society. They all show a negative ROI, which obviously isn't possible. What that indicates is that the savings on equipment within the utility system will be greater than the additional cost of the customer's equipment with the correction installed. To provide a reference, the orange bar shows the ROI with NYSERDA rebates and government tax credits for a solar array with an equivalent power output to the line loss savings from power factor correction. The amount of the rebate is listed above the orange bar. It can be used as a fair comparison to the light blue bar. The red bar shows the return on investment for PV (Photo-Voltaic) solar if there were no government subsidies, to offer a fair comparison to the dark blue bar.

Figure 37 - Power Factor Correction Return on Investment. Service Entrance Correction Systems are not included in the chart because Kvar charges and depreciation are not considered, only energy usage. Without those two cost offsets, the ROI of a service entrance system would be infinite. On a service that is subject to utility Kvar charges, the ROI of the Industrial, Commercial, and Vending Machine categories will be greatly reduced. The amount of the ROI reduction is dependent on the magnitude of the Kvar charge.



Relative Costs of Power Factor Correction 4/18/2010

After market Correction - Joint Public/Private Partnership (Utilities Subsidizing What they would have had to spend on Energy and Equipment)
(Correction added after equipment is in service)

						After market Costs of Correction				Fixed Cost Offsets		Variable Cost Offsets						No Depreciation***	
	Service Size KW	KVAR Added	Demand Reduction (KW)	KWH Reduction (Customer)	KWH Reduction (Utility)	Engineering	Material	Labor	Total Cost	Generation $2000/KW	Substation Capacitance $13/Kvar	Annual Demand $12/KW	KWH Customer $ .20/KWH	KWH Utility $ .05/KWH	Total Cost Offsets (Fixed)	Total Cost Offsets (Variable 1 YR)	NET COST	ROI (Months)	ROI (Years)
Industrial	525	180	7	30000	5200	$6,000.00	$9,000.00	$5,000.00	$20,000.00	$14,000.00	$2,340.00	$1,008.00	$6,000.00	$260.00	$16,340.00	$7,268.00	$3,660.00	6.04	0.503577
Commercial	150	40	1	11400	2630	$6,000.00	$4,000.00	$2,000.00	$12,000.00	$2,000.00	$520.00	$144.00	$2,280.00	$131.50	$2,520.00	$2,555.50	$9,480.00	44.52	3.709646
Vending Machines* (200 machines)	120	100	3.5	16250	12655	$0.00	$14,000.00	$2,000.00	$16,000.00	$7,000.00	$1,300.00	$0.00	$3,250.00	$632.75	$8,300.00	$3,882.75	$7,700.00	23.80	1.983131
Apartments (80 Apartments)	150	30	0.6	1110	1980	$500.00	$4,200.00	$400.00	$5,100.00	$1,200.00	$390.00	$0.00	$222.00	$99.00	$1,590.00	$321.00	$3,510.00	131.21	10.93458

After market Correction - Private Funding Only

						After market Costs of Correction				Fixed Cost Offsets		Variable Cost Offsets						No Depreciation***	
	Service Size KW	KVAR Added	Demand Reduction (KW)	KWH Reduction (Customer)	KWH Reduction (Utility)	Engineering	Material	Labor	Total Cost	Generation $2000/KW	Substation Capacitance $13/Kvar	Annual Demand $12/KW	KWH Customer $ .20/KWH	KWH Utility $ .05/KWH	Total Cost Offsets (Fixed)	Total Cost Offsets (Variable 1 YR)	NET COST	ROI (Months)	ROI (Years)
Industrial	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Commercial	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Vending Machines* (200 machines)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Apartments (80 Apartments)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

*also includes 120 Volt commercial refrigerators

**No Demand Charge Calculation for residential or small commercial. Vending machines in facilities with a large service will see a demand reduction

***Depreciation was not calculated as part of the monetary analysis. Utility $ savings and customer $ savings were added to get the total annual variable cost

The vending machine calculation was done using PLIPs @ $ 70 each plus $ 10 each for installation

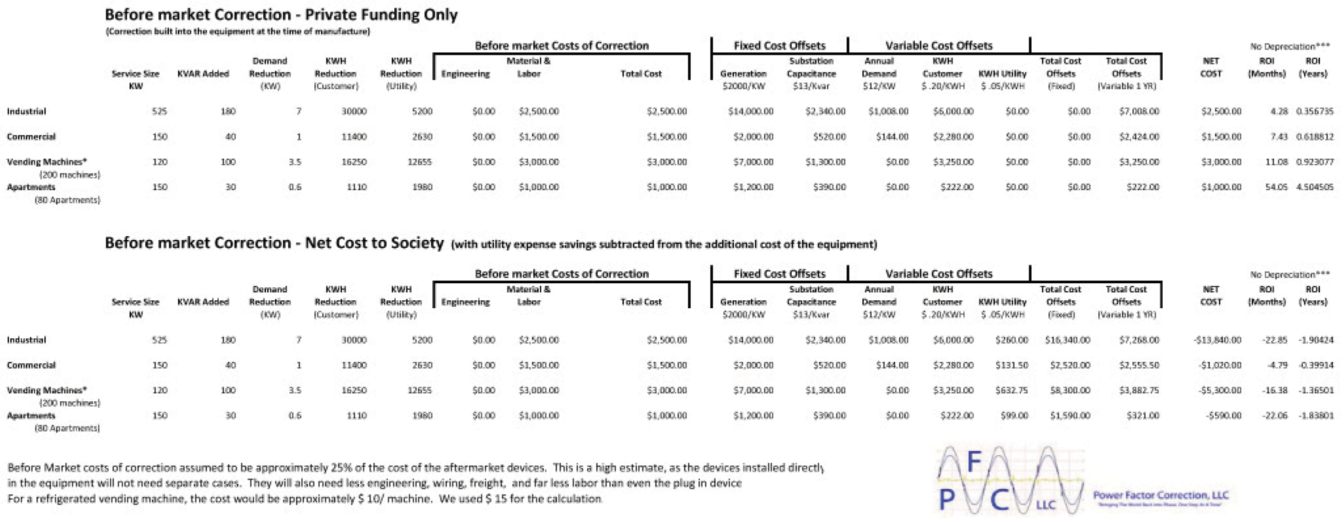
The apartment calculation was done using PLIPs @ $ 70 each plus $ 5 each for installation

$ 70 is the current PLIP cost at smaller production quantities

Industrial location savings based on a 100 hour work week

Commercial location was a supermarket. Refrigeration operates 24/7/365

Figure 38 – Data for Aftermarket Correction Calculations



Before market Correction - Private Funding Only
(Correction built into the equipment at the time of manufacture)

						Before market Costs of Correction			Fixed Cost Offsets		Variable Cost Offsets						No Depreciation***	
	Service Size KW	KVAR Added	Demand Reduction (KW)	KWH Reduction (Customer)	KWH Reduction (Utility)	Engineering	Material & Labor	Total Cost	Generation $2000/KW	Substation Capacitance $13/Kvar	Annual Demand $12/KW	KWH Customer $ .20/KWH	KWH Utility $ .05/KWH	Total Cost Offsets (Fixed)	Total Cost Offsets (Variable 1 YR)	NET COST	ROI (Months)	ROI (Years)
Industrial	525	180	7	30000	5200	$0.00	$2,500.00	$2,500.00	$14,000.00	$2,340.00	$1,008.00	$6,000.00	$0.00	$0.00	$7,008.00	$2,500.00	4.28	0.356735
Commercial	150	40	1	11400	2630	$0.00	$1,500.00	$1,500.00	$2,000.00	$520.00	$144.00	$2,280.00	$0.00	$0.00	$2,424.00	$1,500.00	7.43	0.618812
Vending Machines* (200 machines)	120	100	3.5	16250	12655	$0.00	$3,000.00	$3,000.00	$7,000.00	$1,300.00	$0.00	$3,250.00	$0.00	$0.00	$3,250.00	$3,000.00	11.08	0.923077
Apartments (80 Apartments)	150	30	0.6	1110	1980	$0.00	$1,000.00	$1,000.00	$1,200.00	$390.00	$0.00	$222.00	$0.00	$0.00	$222.00	$1,000.00	54.05	4.504505

Before market Correction - Net Cost to Society (with utility expense savings subtracted from the additional cost of the equipment)

						Before market Costs of Correction			Fixed Cost Offsets		Variable Cost Offsets						No Depreciation***	
	Service Size KW	KVAR Added	Demand Reduction (KW)	KWH Reduction (Customer)	KWH Reduction (Utility)	Engineering	Material & Labor	Total Cost	Generation $2000/KW	Substation Capacitance $13/Kvar	Annual Demand $12/KW	KWH Customer $ .20/KWH	KWH Utility $ .05/KWH	Total Cost Offsets (Fixed)	Total Cost Offsets (Variable 1 YR)	NET COST	ROI (Months)	ROI (Years)
Industrial	525	180	7	30000	5200	$0.00	$2,500.00	$2,500.00	$14,000.00	$2,340.00	$1,008.00	$6,000.00	$260.00	$16,340.00	$7,268.00	-$13,840.00	-22.85	-1.90424
Commercial	150	40	1	11400	2630	$0.00	$1,500.00	$1,500.00	$2,000.00	$520.00	$144.00	$2,280.00	$131.50	$2,520.00	$2,555.50	-$1,020.00	-4.79	-0.39914
Vending Machines* (200 machines)	120	100	3.5	16250	12655	$0.00	$3,000.00	$3,000.00	$7,000.00	$1,300.00	$0.00	$3,250.00	$632.75	$8,300.00	$3,882.75	-$5,300.00	-16.38	-1.36501
Apartments (80 Apartments)	150	30	0.6	1110	1980	$0.00	$1,000.00	$1,000.00	$1,200.00	$390.00	$0.00	$222.00	$99.00	$1,590.00	$321.00	-$590.00	-22.06	-1.83801

Before Market costs of correction assumed to be approximately 25% of the cost of the aftermarket devices. This is a high estimate, as the devices installed directly in the equipment will not need separate cases. They will also need less engineering, wiring, freight, and far less labor than even the plug in device
For a refrigerated vending machine, the cost would be approximately $ 10/ machine. We used $ 15 for the calculation

Figure 39 – Data for Factory Installed (Before Market) Correction Calculations

9.0 Conclusions – Summary of Overall Project

As a result of our measurements taken over the past eighteen months, we have determined the following:

- The power factor is sufficiently low in all of the environments measured that improving it will result in a substantial energy savings throughout the entire utility system, when measured in KWH.

- While aftermarket devices can be used cost effectively to correct power factor in Industrial and Commercial buildings and refrigerated vending machines, as a general rule we **cannot** cost effectively improve the power factor for existing single family homes in the near term using aftermarket devices. In multi-family buildings, depending on the type of mechanical systems, aftermarket devices can be used to cost effectively correct power factor. The longer the cooling season, the shorter the return on investment. In New York City, with many older buildings containing discrete window air conditioners, aftermarket devices are a viable way to quickly reduce load.

- Power Factor Correction is less expensive to implement that most other “Green Technologies” when measured in Kilowatts saved per dollar of investment in all types of buildings except single family homes. It can also be installed in a shorter period of time and is not subject to environmental considerations such as shading or weather.

- Standards need to be modified so that new buildings are designed with a high power factor and a balanced load as part of the design criteria. Communication must be improved between utilities and electrical contractors to ensure that all of the distribution circuits are evenly loaded. Compliance with power factor requirements and balanced load requirements should be verified prior to a Certificate of Occupancy being issued.

- Power Factor Correction, when installed at the load, does not significantly increase the amount of harmonics measured at the utility transformer. Large service entrance correction systems don’t save as much energy as a system installed at the load and also do increase the level of harmonics on the utility system.

- Power Factor Correction must be load based and must only operate when needed. Excess capacitance attached to the utility system can be as detrimental as excess inductance. Furthermore, in the event of a blackout, the excess capacitance would add extra impedance that would have to be energized, applying extra load to the system during a restart.

- Standards need to be modified so that new appliances are required to have a high power factor as part of the design criteria. This is the most cost effective way to reduce energy loss and will save the end user money within two years of purchasing an appliance.

- Standards need to be modified so that new appliances and other electrical devices to be attached to the utility have more strict limits on the amount of harmonics that they generate per watt of consumption. In particular, this will apply to computers, televisions and fluorescent lighting. Harmonics adversely affect electrical efficiency. Furthermore, harmonic mitigation can be very costly to implement. Harmonics are more of an issue, relative to load, in the single family home than in all of the other types of buildings that we measured. As a result, harmonic mitigation will greatly help power quality and reduce losses in single family homes.

In the near term, we can cost effectively correct equipment in the field. During the current recession, the additional work would create jobs that would yield long term positive benefits for the country. The best long-term solution is to have the equipment manufactured properly from the outset so that it has a power factor above 0.97 and a low harmonic discharge. The Department of Energy has to require this as part of the equipment standards. The energy savings and the reduced utility bill will more than pay for the increased costs of Implementing the efficiency improvements.

10.0 Acknowledgements

This project has been partially funded through a grant from the New York State Energy Research and Development Authority (NYSERDA). We thank Michael Razanousky of NYSERDA for the assistance that he has provided for the past eighteen months.

Consolidated Edison Company of New York provided funding and assistance with the installation of meters on the utility poles in the project areas for the single family and multi-family residential phases of this project. We could not have collected the volumes of data that were gathered for the residential phase of the project during the past eighteen months without their assistance with meter installation.

We thank the residents of Hilltop Terrace for their cooperation during the multi-family residential phase of this project.

We thank the owners of Bridge Metal Industries in Mt. Vernon, NY for the use of their facility for the industrial portion of this project.

We thank Peter Plotkin of Superior Vending Machine in Mt. Vernon, NY who permitted measurement of several vending machines at his facility and provided information that confirmed that the results for vending machines that have been presented in this document are not an aberration, and are in fact typical of vending machines presently in use.

We thank Mayor Noam Bramson, Councilperson Marianne Sussman, and the New Rochelle City Council for their efforts during the single family residential phase of the project.

For information on other
NYSERDA reports, contact:

New York State Energy Research
and Development Authority
17 Columbia Circle
Albany, New York 12203-6399

toll free: 1 (866) NYSERDA
local: (518) 862-1090
fax: (518) 862-1091

info@nyserda.org
www.nyserda.org

AT LOAD POWER FACTOR CORRECTION

FINAL REPORT 10-36

STATE OF NEW YORK
ANDREW M. CUOMO, GOVERNOR