At Load Power Factor Correction
Final Report
August 2010

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Energy Research and
Development Authority

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At Load Power Factor Correction Phase 3: Industrial/Commercial

A Pilot Project to determine the feasibility and economics of small scale "At Load" Power Factor Correction

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May 15, 2010

This project was supported by a grant from the

New York State Energy Research and Development Authority [1]

1.0 Introduction, Objectives, and Overview of Phase 3 Results

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 Phase 3 of 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 apartments, residences, commercial and industrial settings. As power factor correction is not a new concept, the project has 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, they do vary from environment to environment. Also, the volume of data being collected and the timeframe of the data collection at the different sites mandate that we divide the project and reports into three phases. This phase of the project focused on "At Load" power factor correction applied to commercial and industrial buildings.

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. [2]

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 harmful harmonics.

2.0 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).

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 their 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.

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, 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.

However, 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.

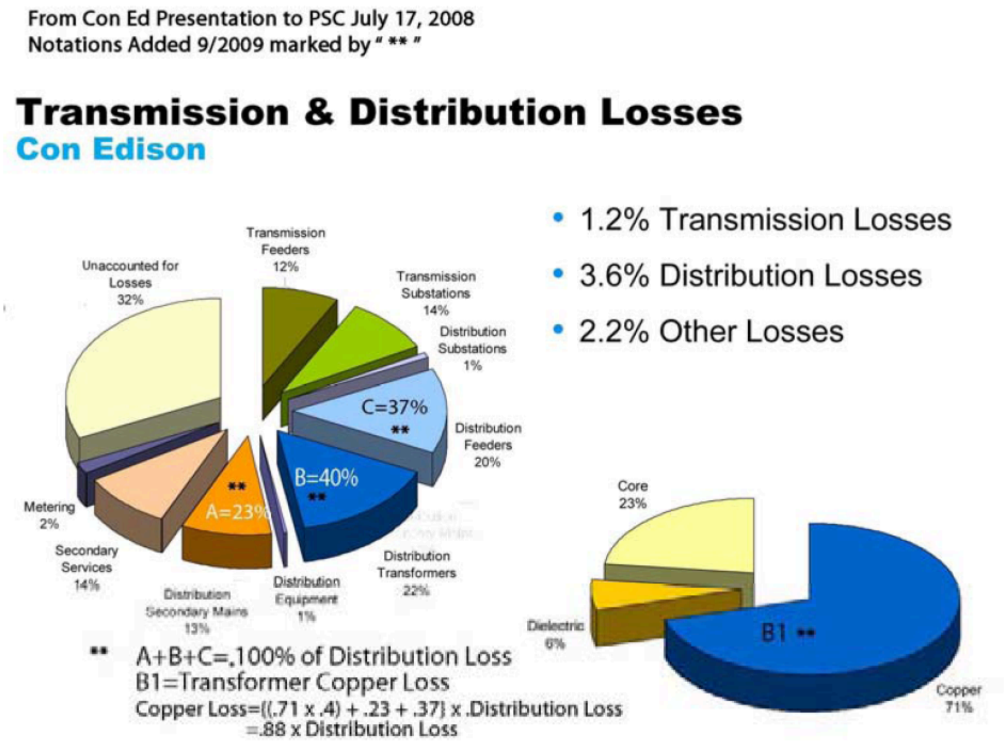


Figure 1: Excerpted from Transmission and distribution Losses. Consolidated Edison. Originally presented July 17, 2008 Percentage Notations added September, 2009.

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 an energy savings. As higher operating temperatures in system components causes 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. 29% 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. 71% of that 40% occurs in the transformer copper, resulting in 28.4% of distribution losses 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[4].

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

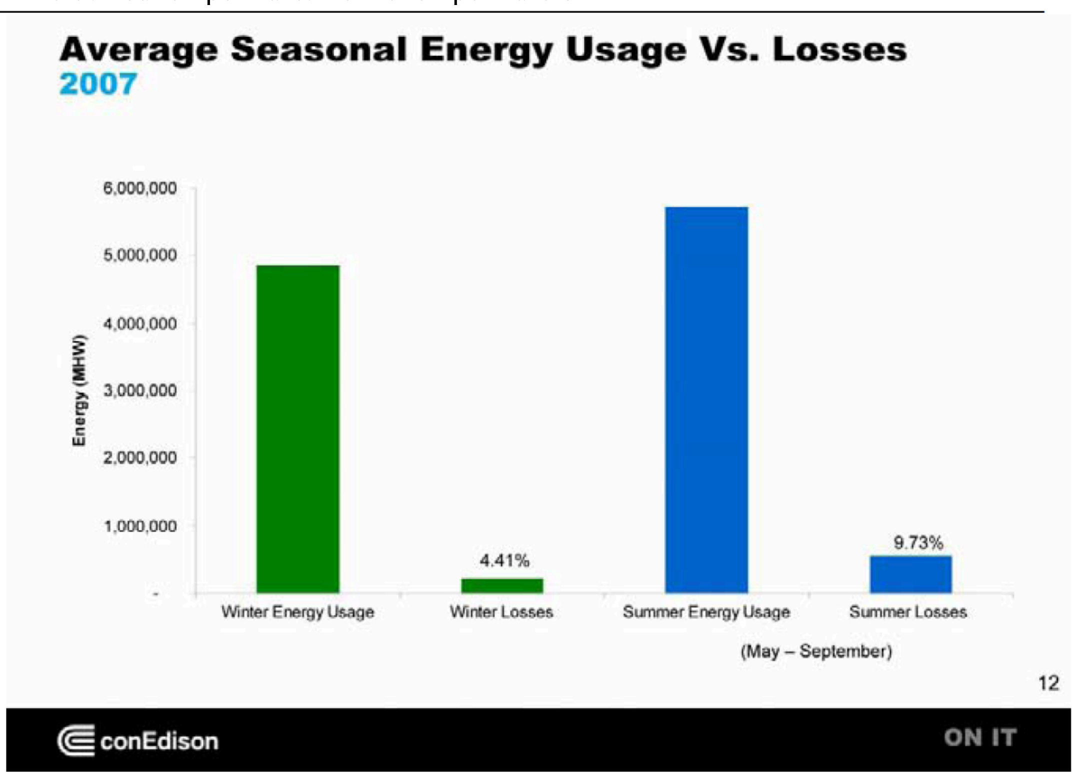


Figure 2: Excerpted from Transmission and distribution Losses. Consolidated Edison. Originally presented July 17, 2008

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

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

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.

[5]

For copper α= 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.

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

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.

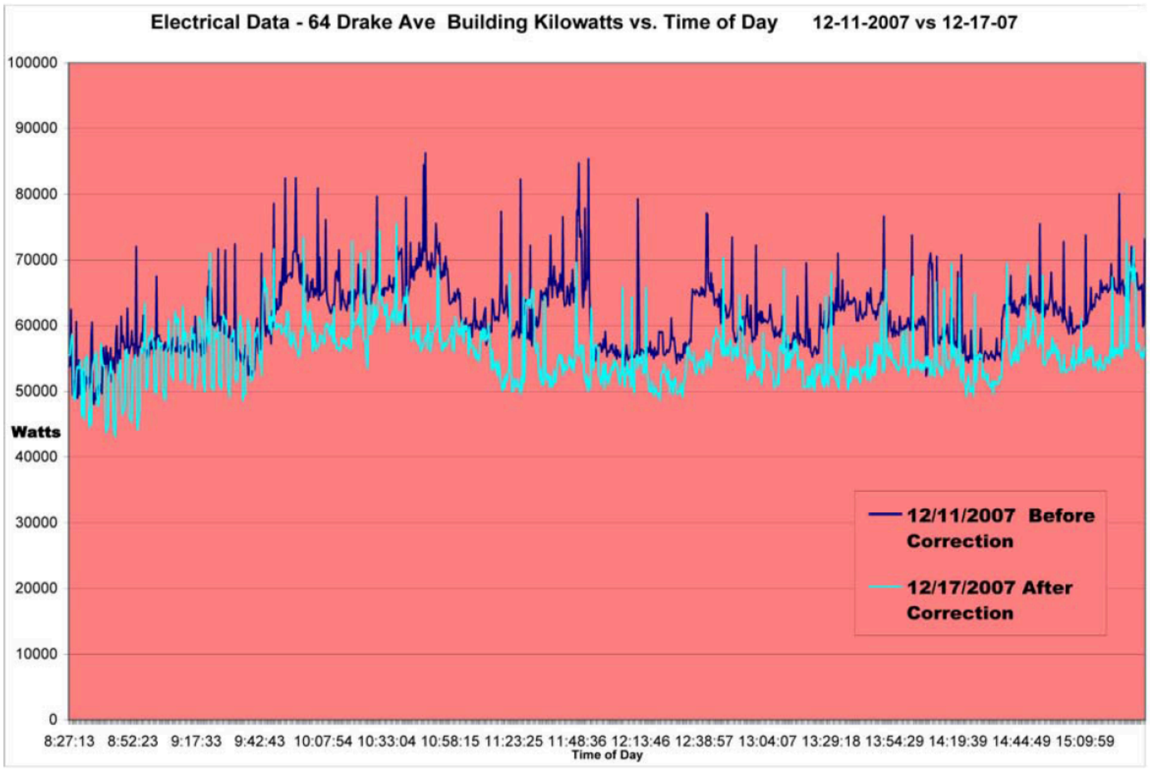


Figure 3 – Customer premise power (KW) usage, before and after reactive power correction. The same equipment was operating on both days, as can be seen from the nearly parallel usage characteristics. The offset is a result of the decrease in consumption caused by raising the power factor from 0.7 to 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 does not 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.

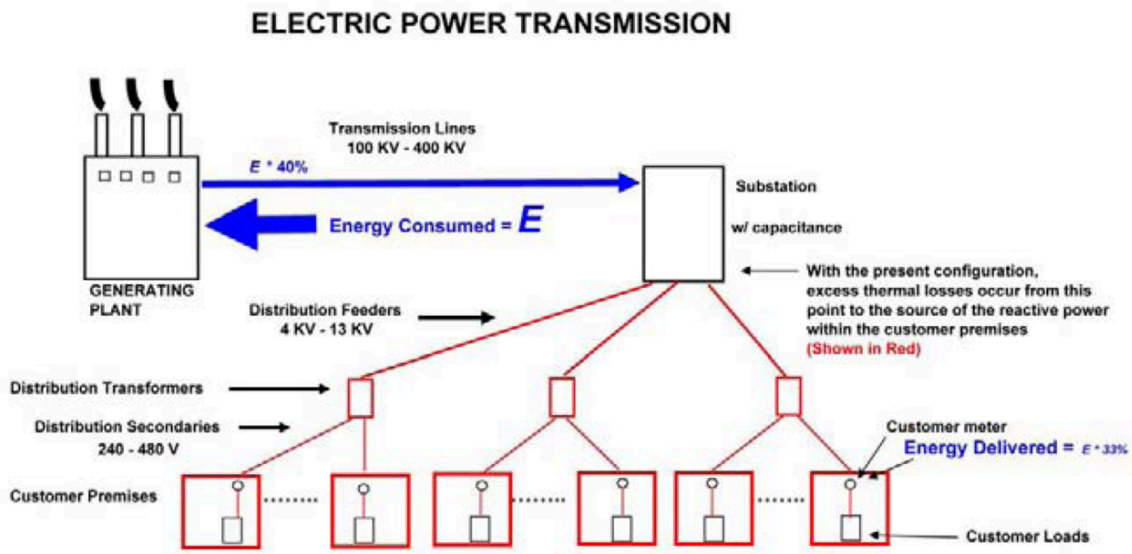


Figure 4 – Block diagram of the electric power transmission system. At present, the utilities correct reactive power at the substations. The distribution system, shown in red, operates with a less than optimal power factor. "At Load" power factor correction will reduce the losses on that entire part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

3.0 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.

4.0 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.

4.1 500 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 0.68	12.44 3 stages 7.4 2 stages	18.21 10.72	5.5 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 $18000, including engineering and installation. That is approximately $3000 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 $2000 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 4 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. 4 volts at 144 amperes on a 3 phase service corresponds to a nearly **1000 watt reduction** in losses in the wires leading to that compressor from the service entrance. That 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 that 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 ten 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 1 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.

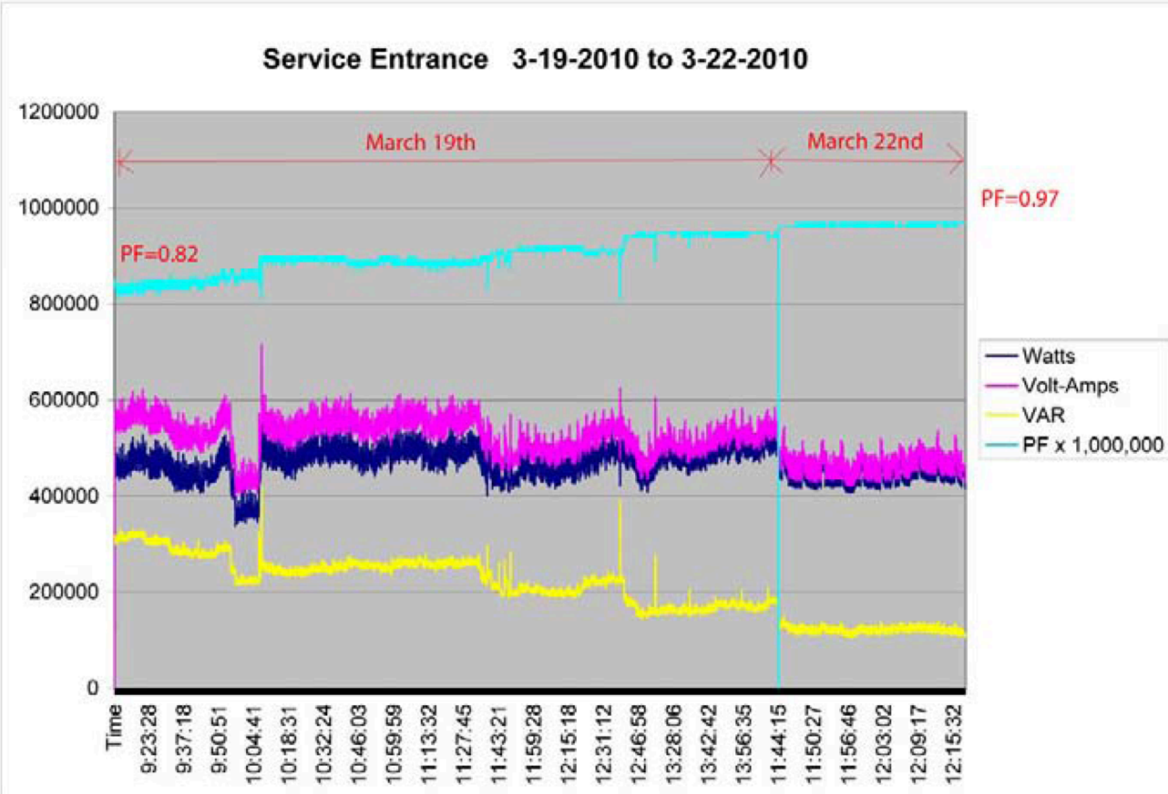


Figure 6 – KW, KVA, Kvar, and Power Factor during turn on of the correction system 180 Kvar of correction was added to raise the power factor from 0.82 to 0.97. Building loads will be reduced by 7 KW to 10 KW as a result of lower currents and the associated reduction in line losses.

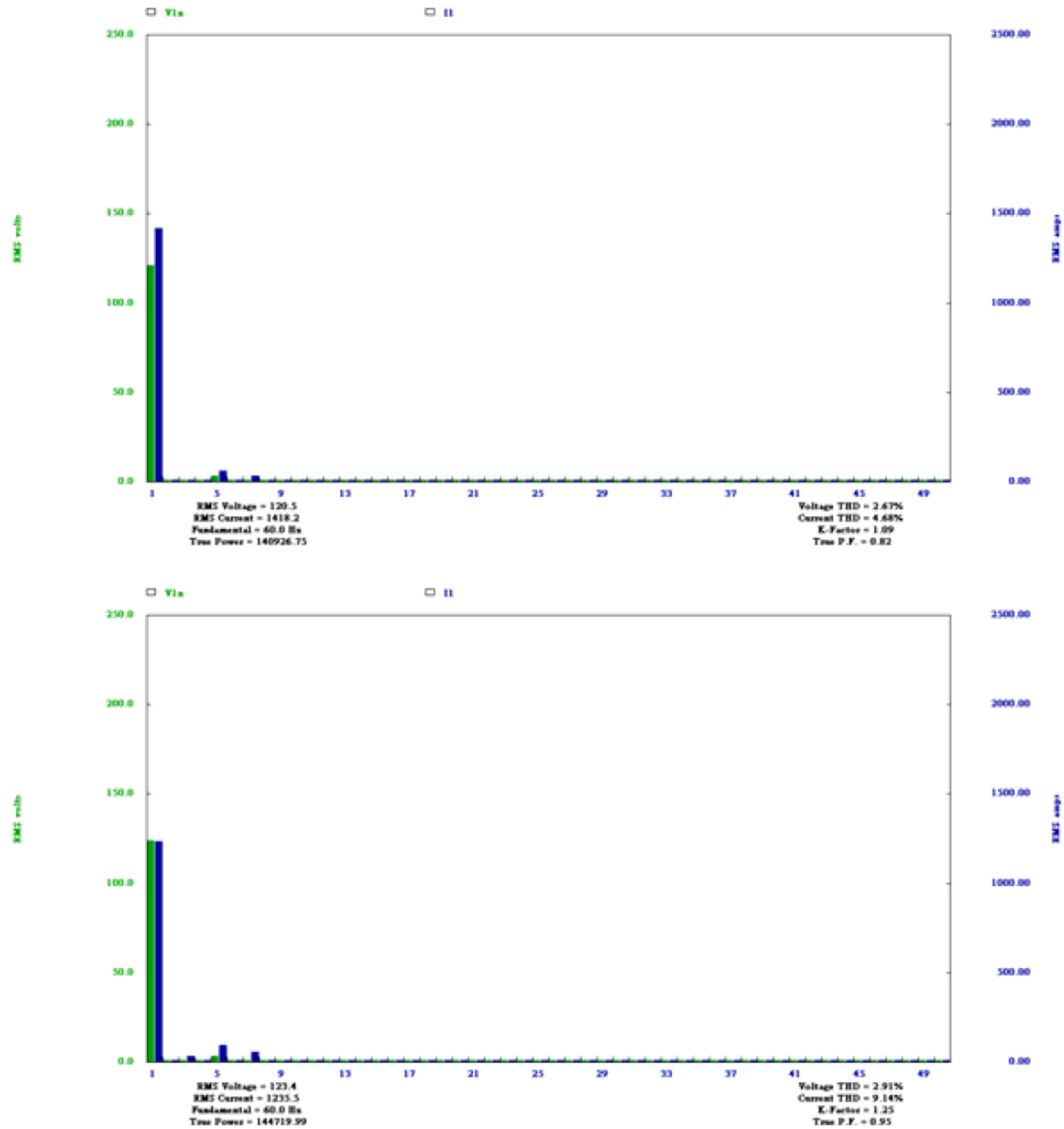


Figure 7 – Harmonics at the service entrance (500 KW facility), before and after correction. Increase in voltage %THD is less than 0.25% after the installation of 180 Kvar of Capacitance. Increase occurs primarily in the 5th and 7th harmonics, with a small increase in the 3rd harmonic.

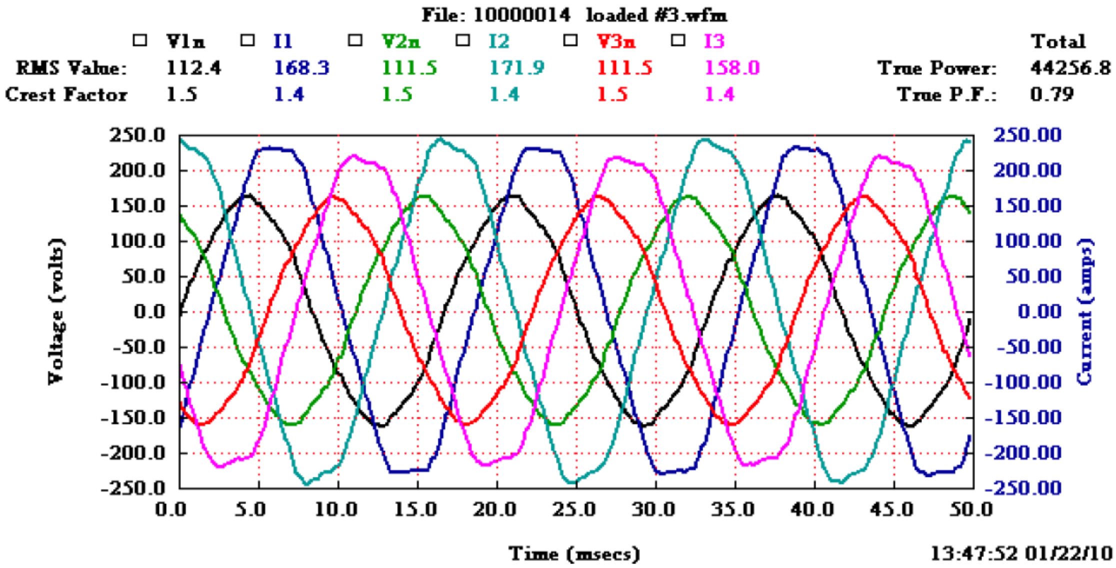


Figure 8 – Waveform of an uncorrected compressor with a power factor of 0.79. After correction, the power factor was raised to 0.96.

4.2 150 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 1KW reduction in demand. The total annual savings on energy costs will be approximately $ 2400 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.

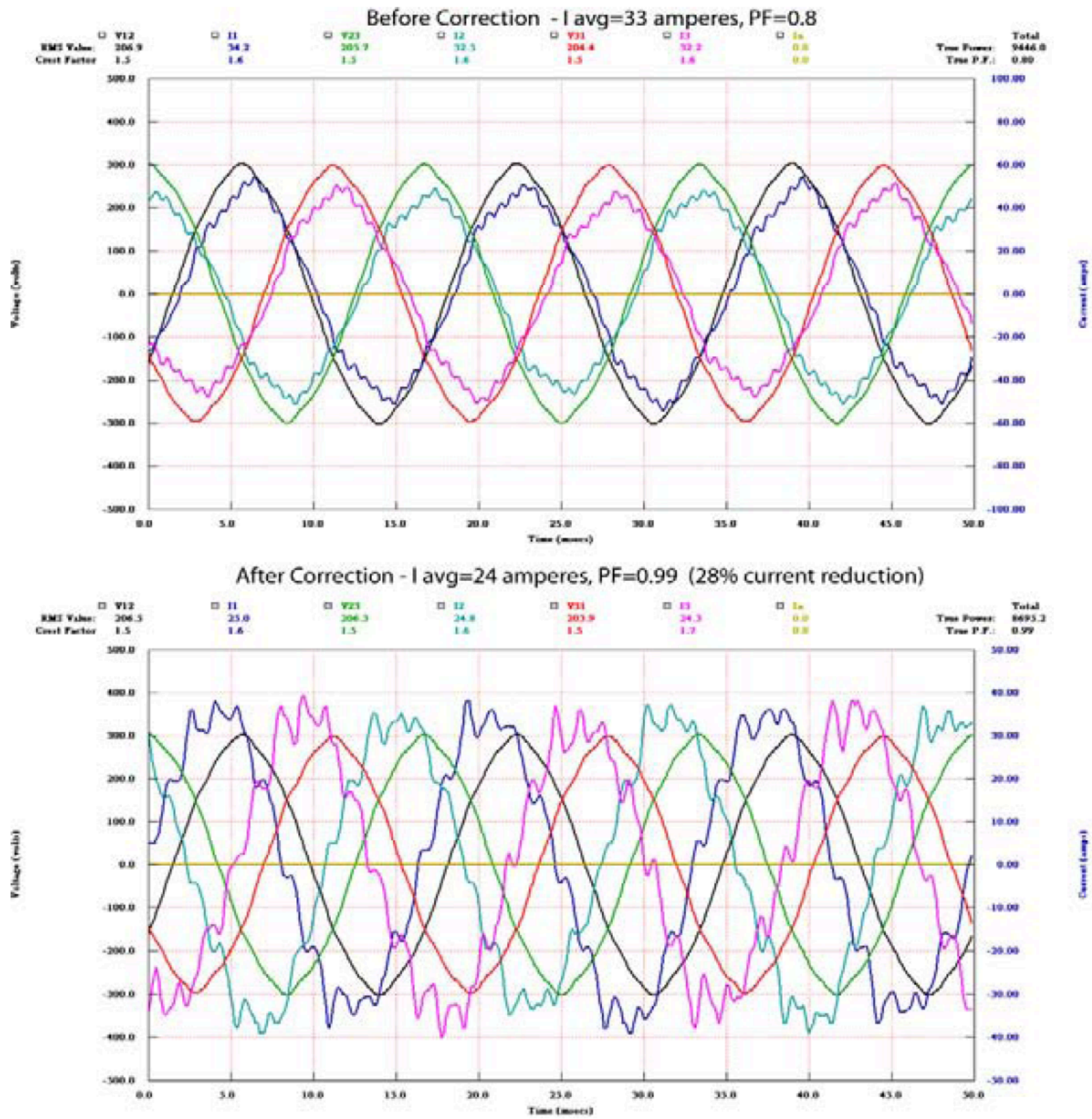


Figure 10 – Before and after waveforms for one of the seven compressors at the supermarket. I_{AVG} was reduced by 28% from 33 amperes to 24 amperes, while the power factor was raised from 0.8 to 0.99. That results in a 48% reduction in associated line losses.

5.0 Cost Benefit Analysis

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

5.1 500 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 $ 2350 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 6 months, when considering the customer premise savings of $ 6000 annually.

5.2 150 KW Facility

The utility system savings for the 150 KW facility are the 2.5 KW generation offset of $5000, 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 $5580 resulting in the net cost of the system being reduced to $6420. With a $2400 after meter annual savings, the return on investment is less than 2.7 years, excluding depreciation.

5.3 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 100KW. However, 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 after market 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. However, simply on an economic basis, the cost effectiveness of this technology justifies its implementation.

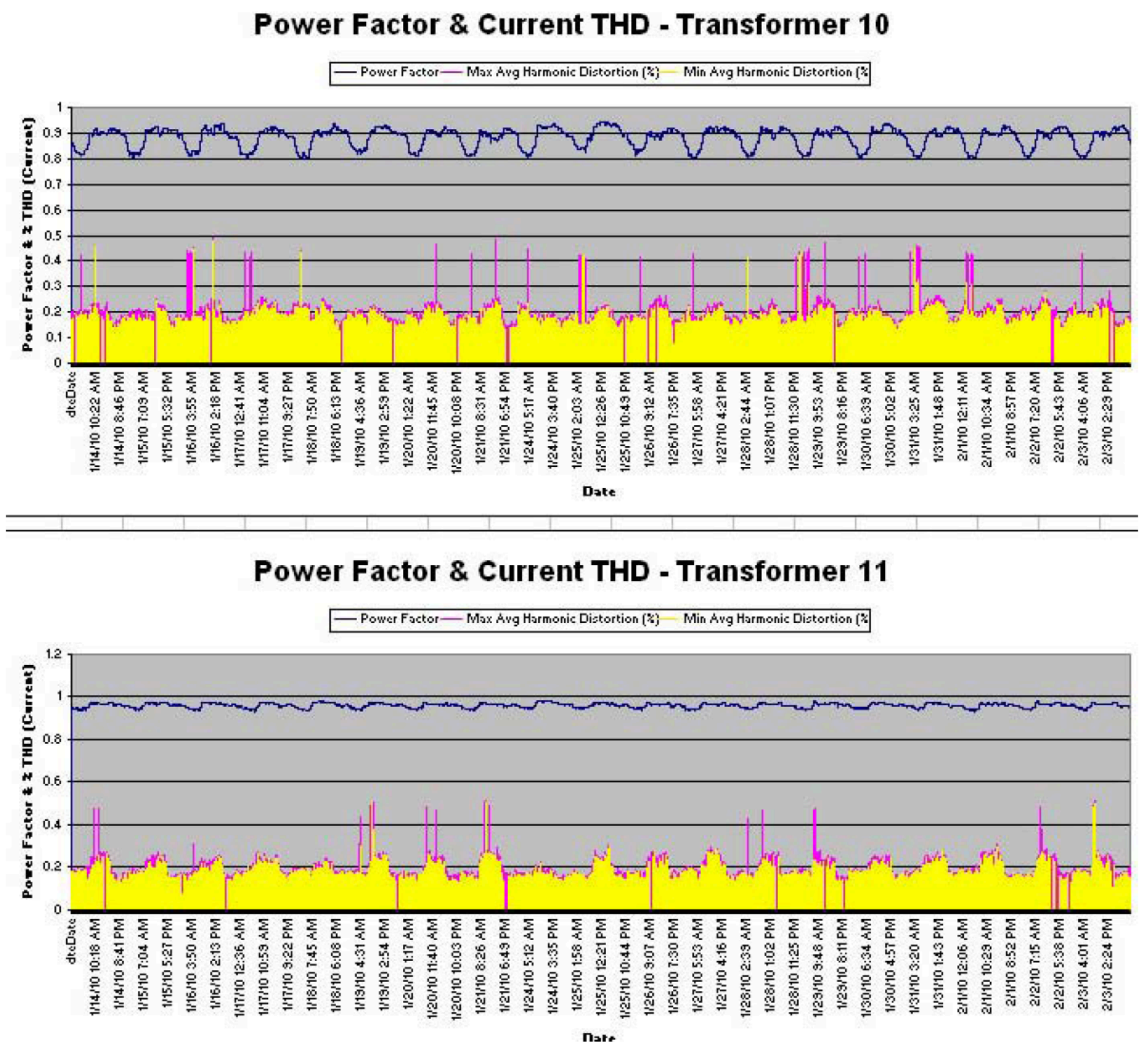
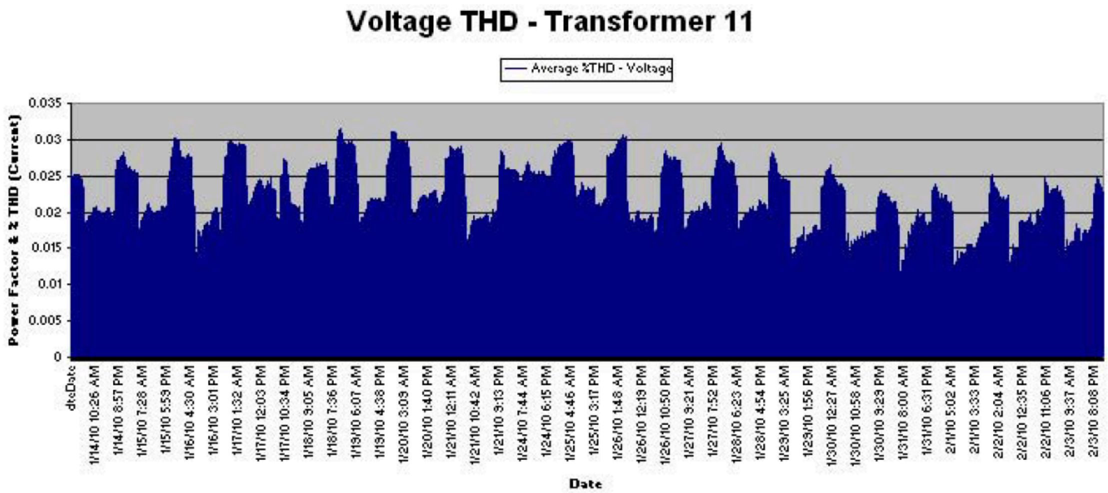


Figure 11 – Power Factor of Two Transformers that share a primary. The apartments attached to transformer 11 have had the power factor raised. Nothing has been done to the apartments attached to transformer 10

6.0 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 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 11 and 12. Figure 11 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 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-1960’s 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 12 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



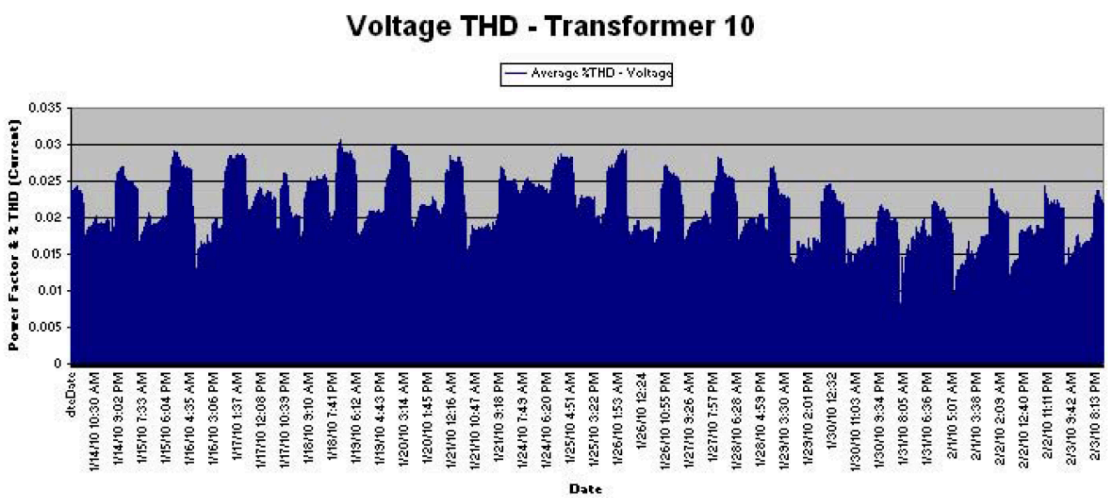


Figure 12 – Voltage Distortion at the secondaries of two transformers that share a primary. The apartments attached to transformer 11 have had the power factor raised. Nothing has been done to the apartments attached to transformer 10.

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 (CFL's), we knew that they would generate significant levels of harmonics. We used twenty 13 watt CFL's on a single phase circuit. The test apparatus is shown in Figure 13. 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 13 – Light Board used to generate harmonics 22

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 14 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%.

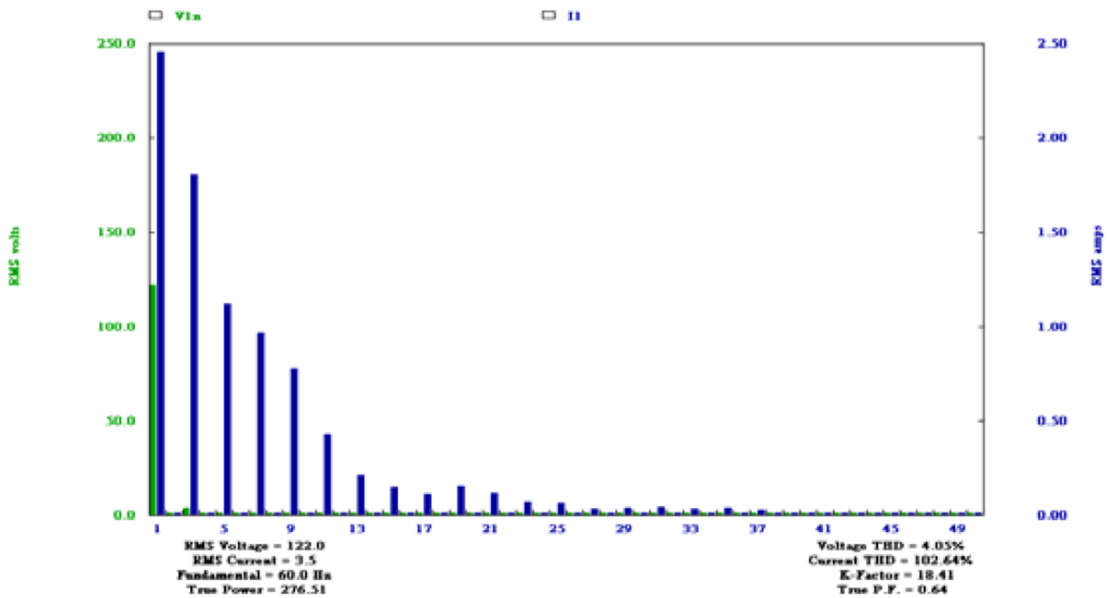


Figure 14 – Harmonic Levels at the contacts of the light board.

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 15, 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 16.

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 15- K-Factor vs. Distance from Harmonic Source

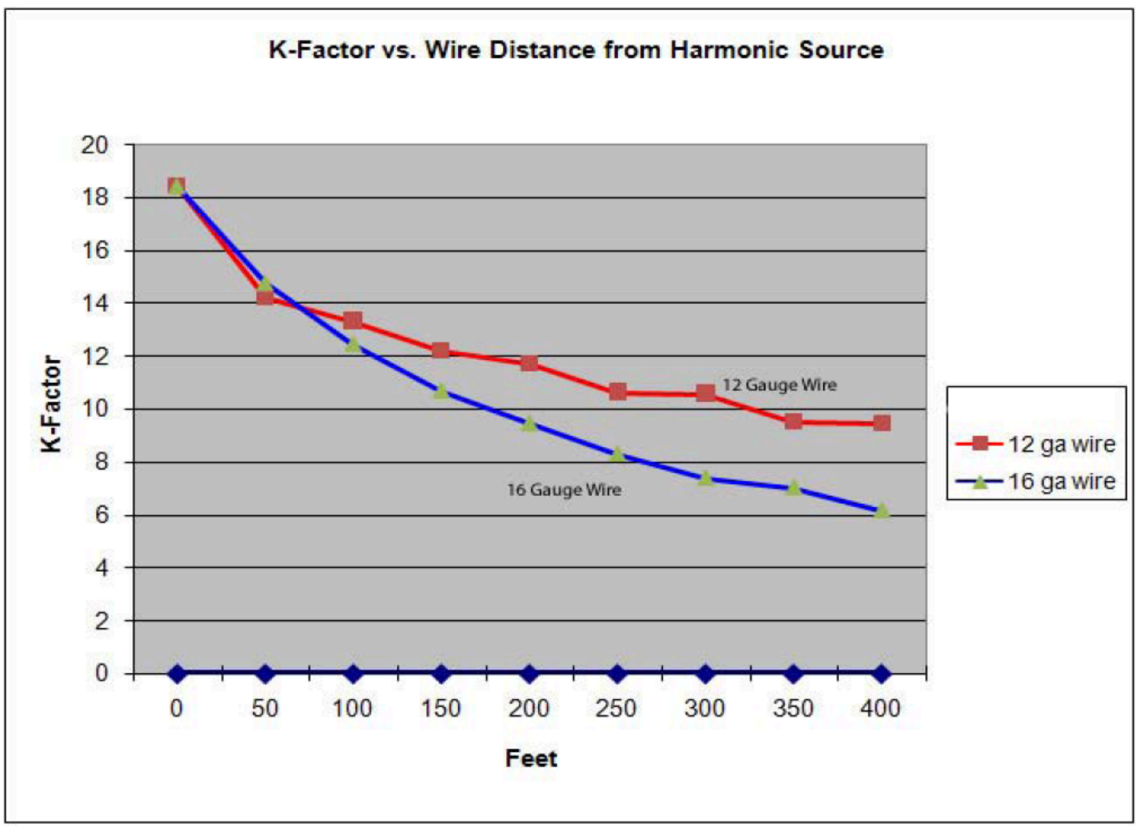


Figure 16 - K-Factor versus distance from the harmonic source .

Figure 17 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 18, 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.

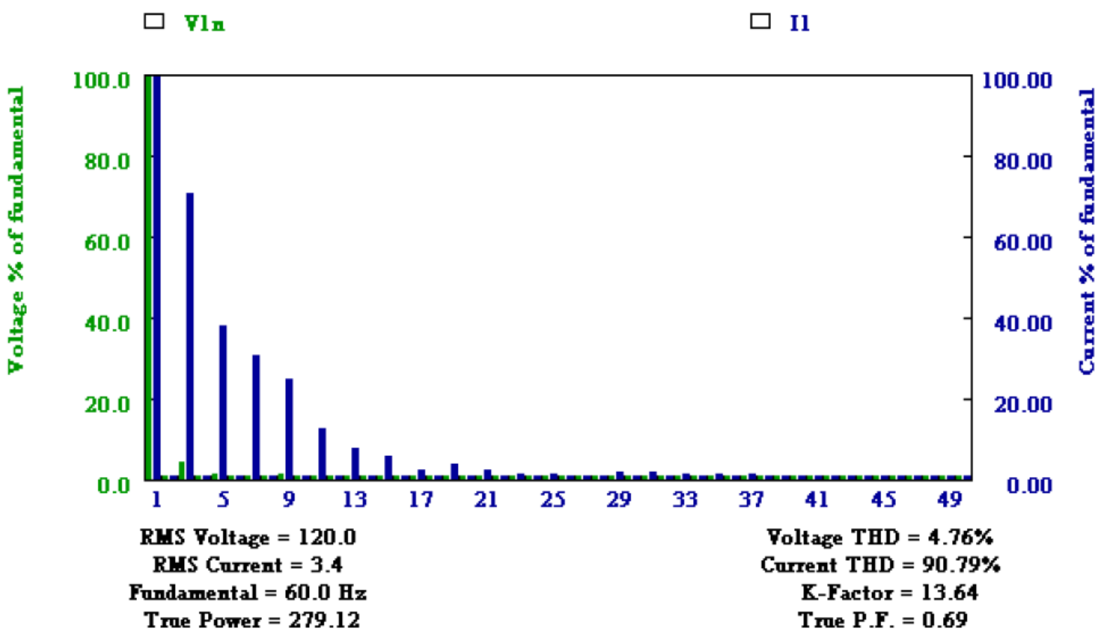


Figure 17 – Harmonic Levels after passing through 100 feet of 12 ga wire

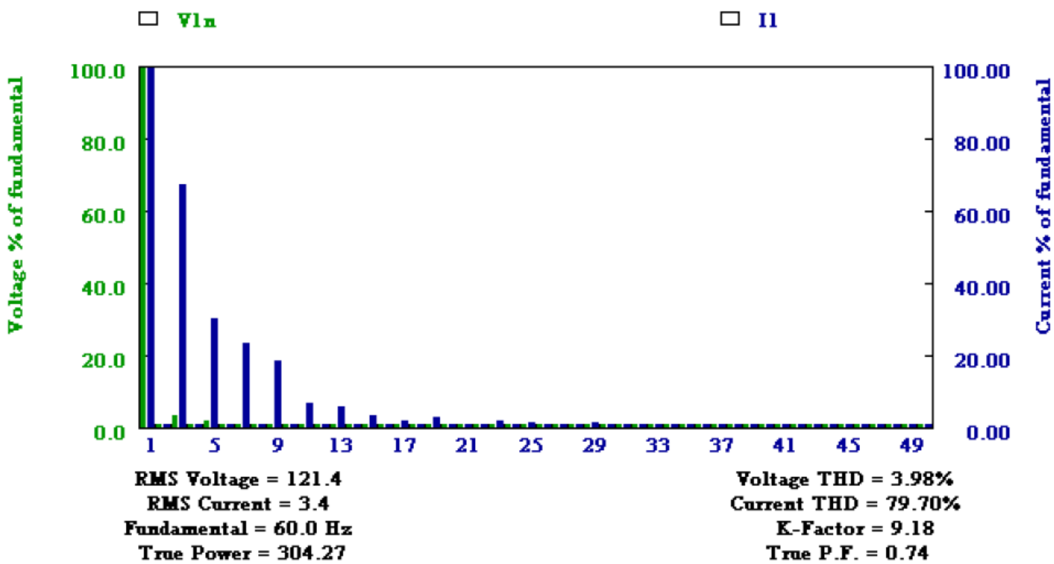


Figure 18 – Harmonic Levels after passing through 400 feet of 12 gauge wire

From the power data, it is also clear that the harmonics are dissipating as thermal losses. In figure 14, 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 16 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. However, 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 CFL's 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. However, 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 2% 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 with various size 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. However, 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 19 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 20 and 21 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 these machines account for. 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. However, it is a widely accepted "green" technology that is heavily subsidized by the government through rebates and tax credits. As such, it makes sense to compare the economics of one technology that reduces utility load at the customer premise to another technology that does the same thing.

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. 29

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% to 33%. 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 300 Kvar 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.

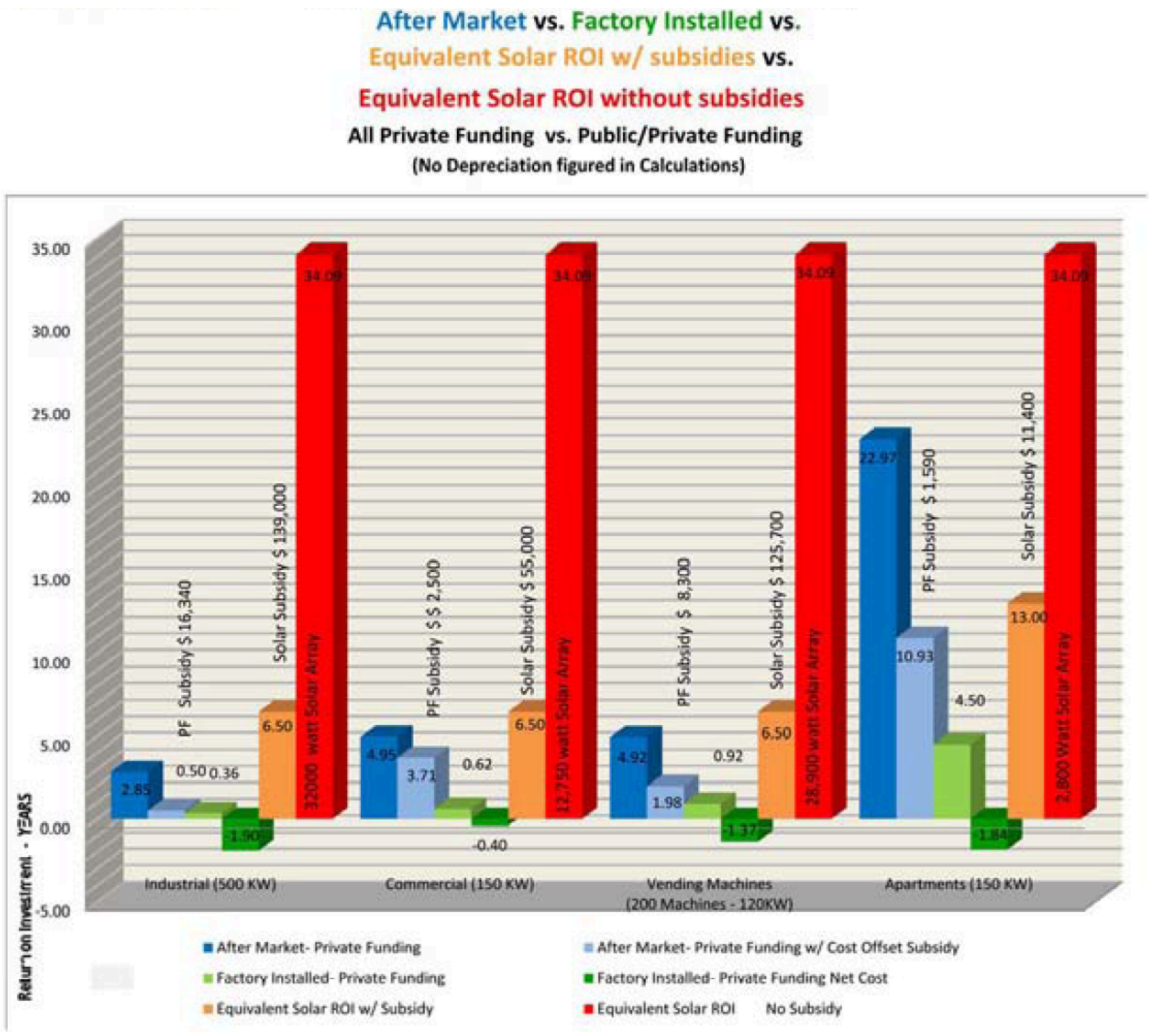


Figure 19 - Power Factor Correction Return on Investment. Service Entrance Correction Systems are not included in the chart because Kvar charges and depreciation are not considered, only energy usage. Without those two cost offsets, the ROI of a service entrance system would be infinite. On a service 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.

9.0 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.

10.0 Acknowledgements

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