Distributed Generation, Customer Premise Loads & the Utility Network A Case Study

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1.0 Introduction and Objective

This paper presents the results of and conclusions from a case study of the interaction between distributed power generation, customer premises loads, and the utility network. Initially, we had only intended to ensure that the two different types of distributed generation at our facility, combined heat and power (CHP) and photovoltaic (PV), worked together in harmony. During that process we derived significant new results about the potential impact of the interconnection of the distributed generation to the utility transmission network (i.e. the grid). These new results led to the writing of this paper. Major conclusions that can be drawn from these results are as follows:

- Distributed generation (DG) within customer premises reduces the power factor at the utility service entrance. Power factor is the ratio of real power on the network to apparent power. The two components of apparent power are real power and reactive power. Real power is the component for which the utility bills its customers. Reactive power is an undesirable byproduct of having inductive loads (e.g. motors and transformers) connected by customers to an AC distribution system. Its characteristic is that the current waveform lags behind the voltage waveform. This results in higher operating currents and higher related thermal losses occurring throughout the system.

- As DG proliferates, with less real power being delivered by the utility and reactive power remaining constant, the power factor of the utility network will decrease and the network may become unstable. The reactive power is not emanating from the DG equipment, but was already present prior to installation of the DG.

- Power factor correction can rectify this problem.

- Power factor correction also can improve the efficiency of the entire utility transmission network and reduce the need for additional large scale generating plants. As a result of the August 2003 Northeast power failure, Con Ed needs to reduce demand by 150 megawatts to ensure system reliability. This is one way to help achieve that goal.

In hindsight, these results seem logical. However, we have been unable to find any reference to similar results or any literature that would have hinted at the magnitude of the improvements in power quality that we have seen as a result of power factor analysis and correction.

These improvements are documented graphically here. All of the graphs included are made directly from raw, unedited data that we collected during the operation of our distributed power generation system, with one exception. Some large transients have been eliminated from the graphs in order to keep the scale readable. Twelve such data points were removed from a total of over 25,000 data points collected and displayed on the graphs.

This paper is addressed at two audiences: those with a background in electrical engineering and those without, who have a need to get a better understanding of the ramifications of their decisions regarding power at their facilities or who need to reduce reactive load at their facilities. It may also be of interest to those who set policy for the utility network. In order to make the material clear to the less technically oriented group, some of the development that follows may seem obvious to the technically savvy. However, the author hopes that the correct balance has been struck so that all readers can gain a clear understanding of the interaction between distributed power generation, customer premises loads, and the utility network. Especially, it is hoped that the power industry will become aware of the likely effects of additional DG on the power network and the need to reduce reactive load on the network.

2.0 Background

Allied Converters is a manufacturing company in Westchester County in the New York City Metropolitan Area. It receives its utility service (electric and gas) from Consolidated Edison (Con Ed). In 2003, two 30 Kilowatt (KW) Capstone natural gas micro-turbines were installed as part of a Combined Heat and Power project (CHP) with partial funding from the New York State Energy Research and Development Authority (NYSERDA). A photo of the CHP System appears in Figure 7. During heating and cooling seasons, the CHP System approaches 68% to 70 % energy efficiency. It is capable of operating both connected to the power grid (i.e., in grid connect mode) during normal operation and stand alone during utility blackouts. It will deliver 45 KW at peak plus 240,000 BTU's of heating or cooling per hour that is captured from the waste heat generated while making electricity. In addition, during the summer of 2007, a 50 KW DC rated photovoltaic solar array was installed on the roof, also with partial funding from NYSERDA. Shortly thereafter, a system also was installed to monitor the electrical output of the solar array, the electrical output of the CHP system and the electrical usage from or back-feed to the grid. A photo of the monitor appears in Figure 5. The inverters on the solar array use the frequency reference from the utility grid to operate while the building is connected to the grid. They use the frequency reference from the micro-turbines to operate when the building is in stand alone mode. The solar array will deliver approximately 43 KW AC at peak output from eight inverters. A photo of the solar inverters appears in Figure 6. A photo of the solar array appears in Figure 12.

The CHP system is set up so as to follow the building electrical load, less 7 KW. The solar array will output at its maximum at all times, based on the time of day, cloud cover, and temperature. Both systems use inverters to provide three phase AC power and track frequency and voltage to match those of the external utility grid. (An explanation of three phase power is available on-line at Wikipedia for those that are unfamiliar with the concept. (http://www.wikipedia.org/). Search for "Three Phase Power".) An inverter uses electronic components to create the AC sinusoidal waveform from a DC supply, whereas a generator uses coiled wire passing through a magnetic field to generate the AC waveform that is common on the utility grid.

The CHP system and solar array at Allied Converters both are working well with the utility grid as measured in terms of this single location, because of its small capacity relative to the entire utility network. However, there are potential problems on the horizon for the network as DG technologies proliferate and deliver a higher percentage of the network's power. With the inevitable arrival of widespread net metering in New York State, alternative energy solutions, many of which are inverter based, will become far more cost effective. While there is certainly a net positive effect from these systems because of the additional efficient power that they provide, there is a downside in that a large number installed under the current installation criteria will eventually affect network stability. This issue must be addressed for locations where these are installed, as well as for the utility grid, in its entirety.

3.0 The Problem

During installation of the solar array at Allied Converters, we were told by the micro-turbine manufacturer that the electricity generated by the solar array would be likely to cause the turbines to go into an over voltage shutdown. If there is too much available power on a network and not enough available load, the voltage on the system will increase. If it increases above allowable set-points, the turbines will shut down. As a first step towards preventing this we installed a system to monitor the following continuously: voltage, current, frequency, power output, reactive power output, and power factor (PF) for all three power sources at our facility (i.e., the CHP system, the solar array and the utility service). The monitoring system is very robust. It includes RS-232, RS-485, and network communications capability, ADC (Analog to Digital) and DAC (Digital to Analog) capability. It also has full digital input and relay output capability, so that building load control also will be possible at a future date, if necessary. The monitoring system can be accessed, read and controlled from remote locations.

During testing of the entire system it became apparent that while in grid connect mode the solar array and micro-turbines would operate perfectly together with no abnormal behavior or shutdowns of the micro-turbines. They have not been tested together in stand alone mode where the over voltage shutdown is a distinct possibility. However, with load control that scenario can be avoided. In stand alone operation, during a failure of the utility network, voltage increase above allowable system limits can be avoided during periods of high solar output by either (a) increasing the building load (e.g. turning on machinery or air conditioning) or (b) turning off some or all of the inverters on the solar array and reducing its power output. This will keep the buildings voltage from rising to a point that would cause the turbine's safety mechanisms to shut them down. In stand alone mode, if the turbines shut down, the solar array will lose its reference and it will shut down as well. That would result in the failure of the backup power system during a blackout. Photos of the protective equipment appear in Figures 8 and 9. The protective relays monitor the power quality and power levels within our facility and on the utility network. The relays will send signals to the transfer switch and main utility circuit breaker to disconnect the building service from the utility network in the event of a utility power failure.

While the problem that we were told to anticipate did not materialize, another potential problem did surface. The factory in which these DG systems are located has several machines with three-phase motors that fluctuate between high and low loads. These include screw -driven air compressors and flywheel-based cutting machinery. Motors operating at light loads, such as those mentioned, will tend to have higher reactive power levels and result in a lower power factor (PF). The building power demand is between 60 KW and 80 KW at various times of the day. The resulting reactive load of the entire facility was between 60 KVAR (Kilo volt-amps reactive) and 80 KVAR. The facility PF was between 0.7 and 0.8. (See figure 1. Description of Power Factor and Reactive Power).

A power factor of 1.0 is the ideal. In that scenario, there is only real power present on the electrical network. As mentioned in the introduction, when reactive power is present, the currents increase in the wiring and in the devices operating on the network. This is undesirable because power dissipation is proportional to the square of the current (I). If the current doubles, power losses within the system increase by a factor of four. Conversely, a current reduction of only 30% will result in a 51 % drop in power losses within the distribution system because $0.7^2 = 0.49$. With little or no reactive power present, the system will operate with little or no heating losses due to excess current.

The power factor of 0.7 that we found at our location, while less than ideal, is not catastrophic for a facility such as ours. However, a problem arises when one takes into consideration the interactions of the local CHP system and solar array with the external electrical network.. Those two sources, together, are designed to produce voltage and current waveforms that precisely follow those of the voltage on the external utility grid and they do so extremely well. The CHP system operates with a power factor of over 0.98 continuously, while the solar array operates with a PF= 0.97 at power outputs above 5 KW and with a PF= 0.98 at power outputs above 7.6 KW. That results in the utility delivering an average of 7 KW when the solar arrays are generating over 10 KW AC. The utility will deliver 17 to 20 KW when the solar arrays are not operating.

Because of the high PF of both of the alternative energy sources while they are operating, the utility was delivering all of the reactive power (KVAR's). This resulted in the utility power factor seen at the building service entrance dropping to between PF=0.1 to PF=0.2. Grid currents of 117 amperes to 120 amperes per phase were measured at the utility service entrance for a building load of only 7 KW. For a comparison, our facility drawing 7 KW with a PF=1.0 would draw only 19 amperes from the grid while our total building current draw with a demand of 65 KW and a PF=1.0 would be 174 amperes per phase. While a PF=0.1 is not a problem if it is isolated to one facility at 7 KW existing on the 12.5 gigawatt Con Ed grid, as these technologies proliferate to many locations, we can expect a drop in the power factor for the entire grid power network and particularly on the local networks near the DG installations. This has the potential to cause instabilities in the electrical transmission network.

There are two factors compounding this problem in the New York metropolitan area. The first is the resistance among citizens to building facilities within the metropolitan area that will add electrical generation capacity. No one wants a generating plant in their vicinity. This has resulted in much of the power being provided from outside of the area. Reactive power is not easily transmitted over long distances because of the additional power losses caused by the higher currents associated with it. These manifest as I^2R (i.e. power dissipation) losses in the cables and transformers in the transmission system and result in additional heat being generated throughout the system. This reduces the efficiency of the entire transmission network.

The second part of the problem has been caused by deregulation. As independent power producers are only paid for KW (real power) delivered and not KVAR (reactive power), they have no incentive to generate the KVAR necessary to operate the inductive loads located throughout the system. These loads include all motors and all transformer based lighting (e.g., fluorescent and metal halide). Because an enormous amount of system load during peak periods is from air conditioning, much of which is powered by electric motors, the potential increase in the ratio of reactive power (KVAR) to KW is of great concern.

4.0 The Solution

When we realized that we had a grid power factor problem at our facility, we undertook a program to reduce the reactive power load locally. To accomplish this, power factor correction capacitors were installed on all of the machinery deemed to be the primary sources of reactive load. These capacitors were installed on the load side of the starters and will function only when the machinery is operating. As mentioned earlier, motors and transformers (which are termed “inductors”) are current storage devices and cause the current waveform to lag behind the voltage waveform. Capacitors do just the opposite. They are voltage storage devices and will cause the current waveform to lead the voltage waveform. They improve power factor by providing a leading power factor to counteract or compensate for the lagging power factor caused by the inductive motor and transformer loads. The amount of those opposite types of reactive power are subtracted from one another, and if they are balanced, all that will remain is the real power to yield a perfect power factor of 1.0 (See Figure 1). Of course, building loads vary, power levels and reactive power levels also change, making it nearly impossible to exactly balance out or counteract all of the reactive power. Thus, a power factor above 0.95 is usually the target for most power factor correction systems.

As an illustration of how this works in practice, the graph in Figure 2 shows the building power levels on December 11, 2007 prior to the installation of correction, while the graph in Figure 3 shows the improvement during and after correction. In both graphs, total building power is in light blue, solar power is in dark blue, utility grid power is in red and CHP power is in yellow. Utility reactive power is in purple. CHP and solar reactive power was too low to measure but were calculated from the power factor of 0.98 to be 1 KVAR at over 45 KW of power output.

After installation of these power factor correction devices, the building PF was raised from PF=0.7 to PF=0.9, the grid PF was raised from PF=0.1 to PF=0.5 and the average per phase grid current was reduced to approximately 45 amperes at a 10 KW grid demand. This was a decrease of approximately 75 amperes (63%) and resulted from the reduction of grid KVARS from 50 KVAR to 70 KVAR prior to correction down to 25 KVAR to 30KVAR after correction. The graph in Figure 3 shows the building power levels during the installation of the power factor correction from December 11, 2007 through December 17, 2007. The initial installation of power factor correction occurred on December 13 and December 14. It was completed on Monday, December 17. The utility reactive power KVAR (purple) can be seen to decrease greatly during this process.

The remainder of the reactive load was variable and from several sources. To correct this, it was necessary to use the power monitor to connect and disconnect additional capacitors, as needed, in response to the varying reactive load. This system of capacitors was connected on the local factory electrical system near the utility service entrance. A four step correction was used with a maximum capacity of 45 KVAR. After implementing this, the average lagging (inductive) power factor was reduced to between 10 KVARS and 15 KVARS. The resulting building power factor is between PF=0.96 and PF=0.99 . The average grid current is now down to approximately 40 amperes per phase at a 10 KW grid demand. The graph in Figure 4 shows the building power levels on January 24, 2008 after the final correction. KVAR levels are further reduced. Some of the higher KVAR levels seen in Figure 4 are actually leading the external network as we were adding capacitance manually to see the net effect. The lagging reactive power levels were in the 10 KVAR to 15 KVAR range.

As a result of the power factor correction, we have reduced our utility grid currents by 75% (120 amperes reduced to 40 amperes) and our overall building current has been reduced from 240 amperes to 160 amperes, a 33% reduction. (See Figure 4) The grid power factor has been raised to between PF= 0.55 and PF=0.7 with the solar arrays and CHP system operating. Harmonic distortion at the utility interface with the power factor correction implemented was 2.5%, as measured by Con Ed. The entire cost of the capacitor correction system was less than $ 7000, including the controller.

5.0 The Bigger Picture

Having seen the success of power factor correction within our facility, we have considered the benefit of similar measures for the overall utility grid. With the proliferation of electronic devices and air conditioning, power demand has increased to a point where the utility managed power network is operating near its limits during the summer months. However, widespread use of power factor correction within the Con Ed service area could increase the efficiency of the system greatly, as well as reduce system demand and help to alleviate the need for additional large generating plants.

Because power is proportional to current squared, a 6% reduction in grid current achieved by power factor correction would result in approximately a 12% reduction in transmission losses caused by the heating of cables and transformers (I^2R losses). Since approximately 8% of all the power generated is lost in transmission, a 12 % reduction in transmission losses would recover nearly 1 % of all the power generated. In Con Ed's 12.5 gigawatt transmission system, that amounts to a savings of almost 125 Megawatts. It might even recover more if losses in the customer facilities after the meter are also taken into account. Correction at each premise load instead of at the service entrance would increase the savings because losses within customer premises also would be reduced. Correction at the service entrance only would reduce the transmission losses.

Table 1 documents the amount of power factor correction needed on a 12.5 gigawatt grid at different power factor levels. Each of the four steps of correction has a different cost and a different payback period. As the grid gets more efficient, the additional correction becomes more expensive, which correlates to what we experienced, on a smaller scale, in our project. The table does not include additional efficiencies that might be gained within the customer premises. It only considers transmission losses. In Table 1, it can be seen achieving a transmission power factor of PF=0.9 from a PF=0.8 on a 12.5 gigawatt grid will reduce the amount of VAR's on the grid by 1.628 gigavar. (Reactive Power Difference). All figures below that row show the associated energy savings from that amount of reactive power reduction and the costs of achieving it through power factor correction versus power plant construction. The energy savings and the CO_2 savings are also calculated.

It would cost Con Ed $ 150 million at $ 1200/kilowatt to construct one large generating plant, the capacity equivalent to the 125 megawatts that is likely to be recovered by power factor correction. To construct smaller, distributed power plants in the New York Metropolitan area would have an even higher cost per kilowatt. To achieve the optimal performance, such a generating capacity would have to be located within the five boroughs of New York City or in Westchester County. However, this would require the use of some of the nation's most expensive real estate. It would also be very likely to gain certain opposition from local groups near whatever site was chosen. To achieve the equivalent current reduction using power factor correction is estimated to cost approximately $ 330 million ($ 100/KVAR). This is 220% more than a new power plant. However, once power factor correction is installed it does not require fuel.

The same 125 megawatts of delivered power one might save with power factor correction would require over 312 megawatts of fuel, assuming a power generation efficiency of 40%. This is slightly more efficient than many of the system's present power plants. That is especially true if one considers the power plants that are used to offset peak loads during the summer months. The general efficiency range is 34% to 38% for a natural gas fired electric generating plant. The 312 megawatts of fuel needed equates to over 900,000 cubic feet of natural gas per hour. With natural gas at a cost of $7.80 per 1000 cubic feet (1 therm=96.7 cubic feet), the savings in fuel amounts to $ 64.5 million annually. The extra $ 160 million needed for power factor correction could be saved in fuel costs alone within less than three years. The entire $ 315 million investment could be offset by reduced energy costs within five years.

That doesn't include savings on the maintenance of the transmission system that will be likely to result from reduced thermal degradation. For example, it was heating of cables that caused the much publicized blackout in Queens in 2006. In general, introducing power factor correction and thereby reducing reactive power levels would improve Con Ed's service, in addition to saving energy and money.

The cited above figures are conservative and estimates are based on installing correction at the service entrance, which will have its primary effect on the transmission network only. Correction at the actual load (motor or transformer) provides a greater benefit to both the utility and the customer than does correction at the service entrance (utility meter). If power factor correction is done properly at the large commercial installations that are the largest users of reactive power, the savings will increase. In that case, more than the transmission system will be positively affected by the reduced reactive power levels. The customer's premises also will have a decrease in reactive power that will result in less heat being generated in the wires and equipment in their facility. That would result in a lower utility bill for the customer and reduced maintenance as a result of less wear and tear on the customer's electrical equipment.

It is generally accepted by engineers in this field that power factor correction can reduce electrical consumption, and the corresponding utility bill by approximately 2% to 4%. There is evidence of this in Graph #2. If the data to the far right on Monday, December 17th (after power factor correction), is compared with the data from December 11th and December 12th to the left of the graph (before power factor correction), it can be seen that the value of the light blue data points has decreased. The light blue data points represent total building real power consumption. 3% to 4% of 60 Kilowatts is in the range of 2 kilowatts which is approximately the amount of decrease on the light blue data points. If the 2% to 4% reduction is extrapolated over a 12.5 gigawatt transmission network, the savings could be an additional 250 megawatts to 500 megawatts beyond the 125 megawatts mentioned earlier, and documented in Table 1. This would require an analysis of larger commercial facilities to accurately correct their power factor at their loads.

Table 2 shows the effect of increasing the power factor during the summer months. It is at this time that the power factor on many areas of the network can drop to PF=0.7 due to the very heavy load applied to the grid by air conditioning. Most of this correction would have to be applied at the air conditioning loads. The per unit cost of correction is higher because the equipment is only used four months per year. However, this is the time of year that most transmission equipment failures and power failures occur. As a result, the actual savings to the system will be much higher than just the energy savings. There will be substantial savings on maintenance of the network. The utility will also be able to decommission its "peak power" plants. Those are the plants that are only used during periods of peak demand. They are the least efficient. Also, as a result of not being used continuously, they have a much higher per unit cost of operation.

In addition, an equitable system of charging for VARS must be implemented so that their true cost to the utility network is applied to those users that have the most demanding loads. That would provide customers with a financial incentive to correct the problem within their facilities.

To reduce the cost of installation across the entire network, one possibility could be a KVAR charge for those customers with a lagging power factor and a KVAR credit for those with a leading power factor. This would have to be regulated by the utility by area so that no section of the network had too much of a leading power factor. That would cause as many thermal losses and inefficiencies as a lagging power factor would cause. A fixed amount of capacitance at a service entrance would eliminate the need for many expensive controllers and a customer would not be penalized for having a *slightly* leading power factor. They actually could install a minimally higher correction than what they need and that would help to compensate for any nearby neighbors that did not perform any correction, reducing implementation costs across the grid. With existing technology, it is possible to install the power factor correction so that it could be controlled remotely by Con Ed, similar to some of the newer thermostats, so that the power factor could be adjusted from a central location if a portion of the network was operating outside of the ideal range.

Furthermore, requirements for equipment connected to the network must be modified so that new equipment that will be installed in the future will have the power factor correction built in. That would make installation simpler, guarantee the most efficient operation of the equipment on the network, and also ensure the largest reactive power savings. While such requirements would increase the cost of the equipment slightly, it would lower the cost of installing the power factor correction, averaged across the entire network. It would also enhance greatly the efficiency of the equipment and make the utility network operate more efficiently, as well.

To put this in perspective, a machine in our facility that would cost nearly $80,000 when new, only needed $450 dollars worth of power factor correction. That would increase the cost of the equipment by only one-half of one percent. It would not be an onerous charge put on the commercial entities that needed new equipment. The additional cost also would be recovered in the form of reduced utility bills.

To avoid unfairly penalizing facilities that have distributed generation on site, the facility power factor would have to be used as the reference, not the utility meter power factor. As seen in Figure 1, a low reactive power at a low power demand can still result in what would normally be considered a poor power factor, even while the actual amount of KVARS is quite low. The normal PF=0.85 or PF=0.9 rule for charging for KVARS would not work for those sites. Efficient DG is an important part of the solution to our energy problems, thus regulators should be careful not to create an environment that discourages their implementation and operation.

We also have installed a similar monitoring system in a residence. Based on this experience, we estimate that the average home could be corrected with 1 KVAR or 2 KVAR of capacitance without doing an elaborate analysis of each home individually. This capacitance would offset the effects of reactive power resulting from the presence of refrigeration and air conditioning and would cost a few hundred dollars per home. Homes with larger refrigeration loads and larger air conditioning loads would need additional correction, primarily at the air conditioner power connection.

For example, a 5 ton air conditioning unit could require as much as 3 KVAR to 5 KVAR of correction. If this was installed when the unit was installed, it would have no negative effect on system power factor and would operate more efficiently. The same thermostat signal that started the compressor could close a contact that would implement the correction. Correction of air conditioning reactive loads is especially critical, because these apply their maximum demand when the utility distribution network is under the greatest stress. Based on discussions of this situation with knowledgeable field technicians that specialize in electrical testing, the power factor on portions of the transmission network can drop to as low as PF=0.7 to PF=0.75 on hot, humid summer days when the air conditioning load reaches its peak. This accounts for many of the localized transformer and cable failures that receive so much attention in the media.

Table 1, which documents potential energy savings that would result from widely adopted power factor correction, only documents savings down to a power factor of PF=0.8. Corrections of power factors below that level are even more cost effective and require a shorter timeframe to recoup the investment. They also yield greater energy savings per dollar spent along with a higher reduction of CO_2 emissions per dollar spent. Table 2 documents the additional savings that will result from additional power factor correction from PF=0.7 to PF=0.8.

We have been trying to understand why the power factor problem has not been analyzed at an earlier date because the technology needed to rectify it is not new. We believe that there are three main reasons.

First, since distributed small scale generation is a relatively recent phenomenon, the interaction of DG with the utility networks has not been closely studied. The utility interconnection agreement requires that the DG has a high power factor. All those asked, stated that distributed generation with a high power factor would actually improve the power factor of the utility network. In fact, just the opposite occurs when the DG is located within the utility's distribution area.

Second, since deregulation, Con Ed and all utilities in New York State are responsible for power distribution and not power production. When they were generating their own electricity 10 years ago, while power factor correction would have saved a great deal of energy, fuel costs were low and this process would have been cost prohibitive. An analysis done at that time would have shown a cost with a twenty to thirty year return on investment. This would not have been sufficient incentive to attract the necessary capital Further, as the demand on the utility network was much lower at that time, the need was not there. It is only the recent increase in energy costs that have made power factor correction so cost effective. In addition, the robust New York City economy with its higher electric demand has made it essential.

A third reason why power factor correction has not drawn more attention is that the independent power producers are not paying for the inefficiencies. Any power losses after the customer's meter results in more revenue for them. The costs caused by inefficiencies on the utility grid are reflected in the distribution costs that appear on Con Ed customer utility bills. These are not unreasonable charges, as the costs are actually being incurred by the utility. However, the economic realities have changed. Now, it is both financially advantageous and environmentally imperative that the situation be rectified in order to make the network more efficient.

6.0 Conclusions

Alternative energy sources such as CHP Systems, photovoltaic solar arrays and wind power are an essential part of an overall plan to reduce the nation's energy consumption. However, power factor correction must be performed on sites where these technologies are installed in order to prevent future stability problems on the utility network as the technologies proliferate.

On a larger scale, power factor correction has the potential to increase the efficiency of the entire electric transmission system. It could reduce the Con Ed system load by over 100 megawatts, and possibly by 250 megawatts to 400 megawatts. It also would increase system efficiency, reduce network maintenance costs, and help to alleviate the need for additional generating capacity for the New York City metropolitan area. It is very likely to improve Con Ed's delivery system, save an enormous amount of energy, and would also be likely to reduce significantly the carbon footprint of generated power in the metropolitan area

An equitable system of charging for VARS should be implemented that accurately reflects their cost to the system and provides an incentive for customers, particularly the large power customers, to perform power factor correction. For locations that have a distributed generation system on site, that would include looking at the facility power factor and not just the power factor at the utility meter. Public policies and regulations also should be implemented to encourage utility customers to pursue power factor reduction within their premises.

The New York State codes should be modified so that all new electrical equipment with a high reactive power requirement introduced into the state, has the power factor correction built in. If this is done by the equipment manufacturer, it will be far easier to maintain a higher standard of quality power on the utility network. Installation of the requisite capacitors in the equipment is far simpler and less expensive to do at the time of their manufacture, than later in the field. Having the power factor correction built into the equipment would also prevent anyone that is trying to cut costs, from doing so at the expense of not performing the necessary power factor correction.

Raising the power factor within customer premises will improve power quality within the entire transmission network and result in the following:

- Reduced power losses on the utility transmission network and within customer premises
- Reduced thermal degradation of transmission system equipment and customer premise equipment.
- Improved service through fewer system failures (i.e. failed transformers and cables).
- Reduced system wide costs as a result of lower energy usage.
- Reduced losses on the transmission network will result in a greater capacity for real power (KW) distribution. This will allow Con Ed to deliver more power with the existing network without adding additional transmission capacity.
- Lower customer utility bills that will offset the cost of implementation of the power factor correction.
- Greatly reduced greenhouse gas emissions of the New York City and Westchester area by a significant amount through lower power consumption.

7.0 Acknowledgements

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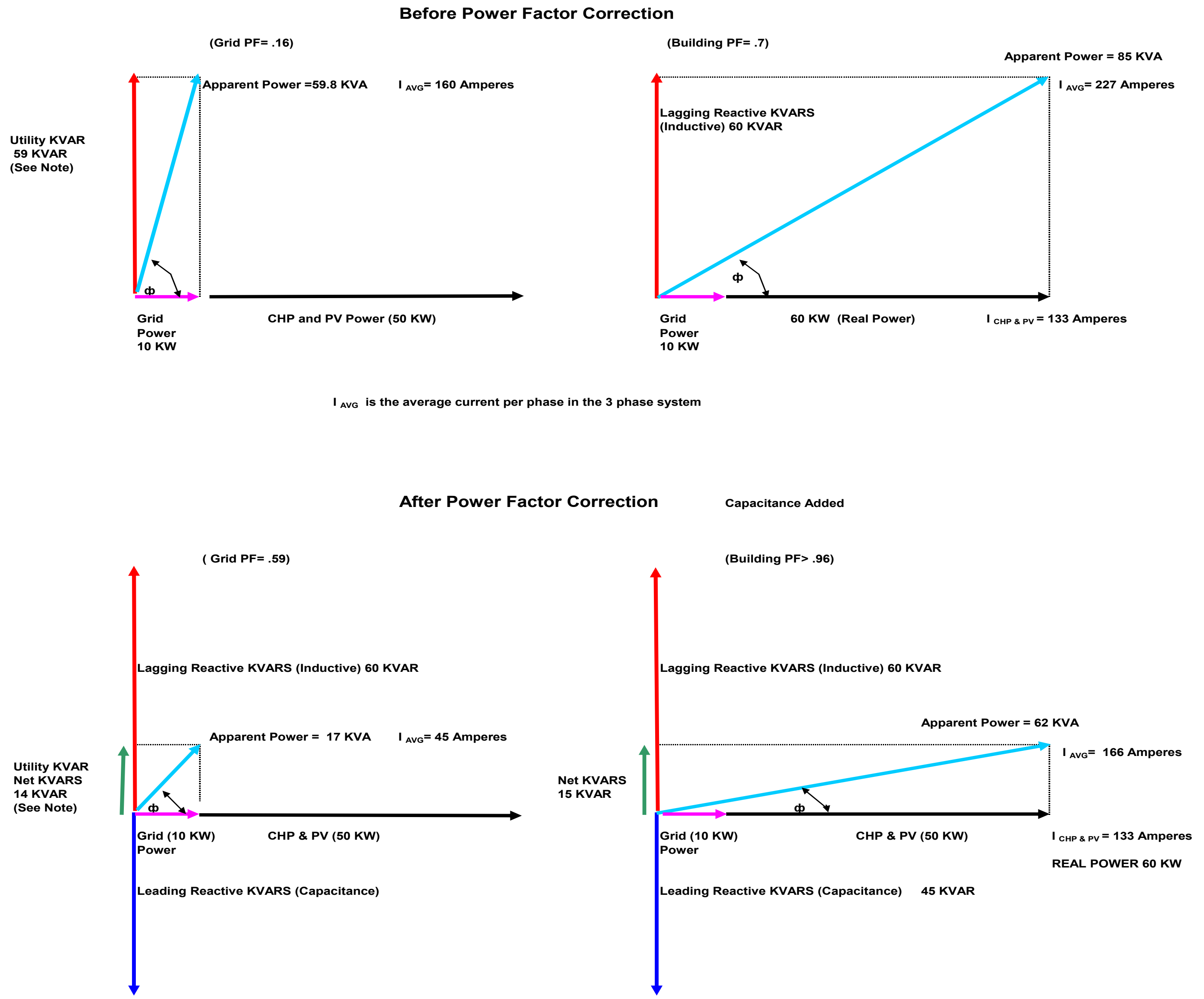
Figure 1: Power Factor Correction Explained



PF=cosine ф = Real Power (KW) / Apparent Power (KVA)

Lagging Reactive Power is a result of having motors and transformers (Inductive Loads) in a circuit. They are current storage devices and will cause the current peak to trail behind (lag) the voltage peak during the AC cycle

Leading Reactive Power is the result of having capacitors in a circuit. They are voltage storage devices and will cause the voltage peak to trail behind the current peak during the AC Cycle. Since the voltage is used as the reference, the net effect is that they cause the current to lead.

Voltage (V) is constant = 216 Volts phase to phase in a 3 phase system.

Apparent Power (P) = √3 * I * V (1.73 * Current (I) * Voltage (V)) = 1.73 * 216 * I

As apparent Power decreases due to correction, current (I) will drop proportionally

Note : With a PF=.98 the CHP and PV Systems will provide approximatly 1 KVAR of reactive power at 50 KW of output

Values Chosen are for example only but are representative of the effect that we have seen at our facility.

Table 1 - The costs and benefits of power factor reduction on the Con Ed transmission network

	Step of Reduction	0	1	2	3	4
	Grid Power Factor	0.8	0.85	0.9	0.95	1
	Real Power (12.5 gigawatts) Watts	12,500,000,000.00	12,500,000,000.00	12,500,000,000.00	12,500,000,000.00	12,500,000,000.00
	Apparent Power (VA)	15,625,000,000.00	14,705,882,352.94	13,888,888,888.89	13,157,894,736.84	12,500,000,000.00
	Reactive power (VAR)	9,375,000,000.00	7,746,804,230.04	6,054,026,310.47	4,108,551,314.74	0.00
	Reactive power difference (VAR)	NA	1,628,195,769.96	1,692,777,919.57	1,945,474,995.74	4,108,551,314.74
	% power reduction (1 - % power reduction)	NA	0.941176471	0.944444444	0.947368421	0.95
	% current reduction (1 - % current reduction)	NA	0.9701425	0.971825316	0.973328527	0.974679434
NOTE 1	**power loss reduction** (based on 8% transmission loss)	NA	0.004705882	0.004444444	0.004210526	0.004
	KW saved on grid	NA	58,823.53	55,555.56	52,631.58	50,000.00
NOTE 2	**energy saved-KW** (40% Plant efficiency)	NA	147,058.82	138,888.89	131,578.95	125,000.00
	Therms saved per hour	NA	5,019.07	4,740.24	4,490.75	4,266.21
	1000 CF Nat Gas saved per hour	NA	485.40	458.44	434.31	412.59
	$$ Nat Gas Saved/Year ($ 7.80/1000 CF)	NA	$ 33,166,652.23	$ 31,324,060.44	$ 29,675,425.68	$ 28,191,654.40
	Cost of Generating Plant of same capacity ($ 1200/KW)	NA	$ 70,588,235.29	$ 66,666,666.67	$ 63,157,894.74	$ 60,000,000.00
	Cost of Power Factor Correction ($ 100/KVAR)	NA	$ 162,819,577.00	$ 169,277,791.96	$ 194,547,499.57	$ 410,855,131.47
	Difference	NA	$ 92,231,341.70	$ 102,611,125.29	$ 131,389,604.84	$ 350,855,131.47
	Years to payback when compared to generating plant	NA	2.78	3.28	4.43	12.45
	Years to payback overall	NA	4.91	5.40	6.56	14.57
	Therms saved per year	NA	43,967,075	41,524,460	39,338,962	37,372,014
	1000 CF Nat Gas saved/year	NA	4,252,135	4,015,905	3,804,542	3,614,315
NOTE 3	**tons CO2 not released each year into atmosphere**	NA	65,951	62,287	59,008	56,058

Assumptions:

* **12.5 gigawatt real power**
Note 1 **8% Transmission losses**
Note 2 **40% Natural gas plant efficiency - from Gas to Kw at plant interface to grid. If 35% power plant efficiency is used, the payback periods are reduced by approximately 8 months.**
Note 3 **1000 therms of burned Natural gas emits 1.5 tons of CO2 into the atmosphere.**
* **Each column calculates the amount of correction and the cost needed to get to that value from the column to the left of it.**
* **Cost of Natural gas used was $ 7.80 per 1000 cubic feet from DOE web site May 2007 price - power generation pricing ($ .75/therm)**
* **Only gas costs are figured in the payback period for the power factor correction. It does not include reduced maintenance costs that will result from the lower currents.**
* **It also does not include the lower carbon footprint that will result from less burning of fossil fuels.**

Table 2 - The costs and benefits of power factor reduction for four months during the summer

	Step of Reduction	**0**	**1**	2
	Grid Power Factor	0.7	0.75	0.8
	Real Power (12.5 gigawatts) Watts	12,500,000,000.00	12,500,000,000.00	12,500,000,000.00
	Apparent Power (VA)	17,857,142,857.14	16,666,666,666.67	15,625,000,000.00
	Reactive power (VAR)	12,752,550,765.26	11,023,963,796.10	9,375,000,000.00
	Reactive power difference (VAR)	NA	1,728,586,969.15	1,648,963,796.10
	% power reduction (1 - % power reduction)	NA	0.933333333	0.9375
	% current reduction (1 - % current reduction)	NA	0.966091783	0.968245837
NOTE 1	**power loss reduction** (based on 8% transmission loss)	NA	0.005333333	0.005
	KW saved on grid	NA	66,666.67	62,500.00
NOTE 2	**energy saved-KW** (32% Plant efficiency)	NA	208,333.33	195,312.50
	Therms saved per hour	NA	7,110.35	6,665.96
	1000 CF Nat Gas saved per hour	NA	687.65	644.68
	$$ Nat Gas Saved/Year ($ 7.80/1000 CF)	NA	$ 15,662,030.22	$ 14,683,153.33
	Cost of Power Factor Correction ($ 100/KVAR)	NA	$ 172,858,696.92	$ 164,896,379.61
	Years to payback overall	NA	11.04	11.23
	Therms saved per year	NA	20,762,230	19,464,590
	1000 CF Nat Gas saved/year	NA	2,007,953	1,882,456
NOTE 3	**tons CO2 not released each year into atmosphere**	NA	31,143	29,197

Assumptions:

* **12.5 gigawatt real power**
Note 1 **8% Transmission losses**
Note 2 **32% Natural gas plant efficiency - from Gas to Kw at plant interface to grid. Considers efficiency of plants only used during peak load periods These are the least efficient power plants.**
Note 3 **1000 therms of burned Natural gas emits 1.5 tons of CO2 into the atmosphere.**
* **Each column calculates the amount of correction and the cost needed to get to that value from the column to the left of it.**
* **Cost of Natural gas used was $ 7.80 per 1000 cubic feet from DOE web site May 2007 price - power generation pricing ($ .75/therm)**
* **Only gas costs are figured in the payback period for the power factor correction. It does not include reduced maintenance costs that will result from the lower currents.**
* **It also does not include the lower carbon footprint that will result from less burning of fossil fuels.**

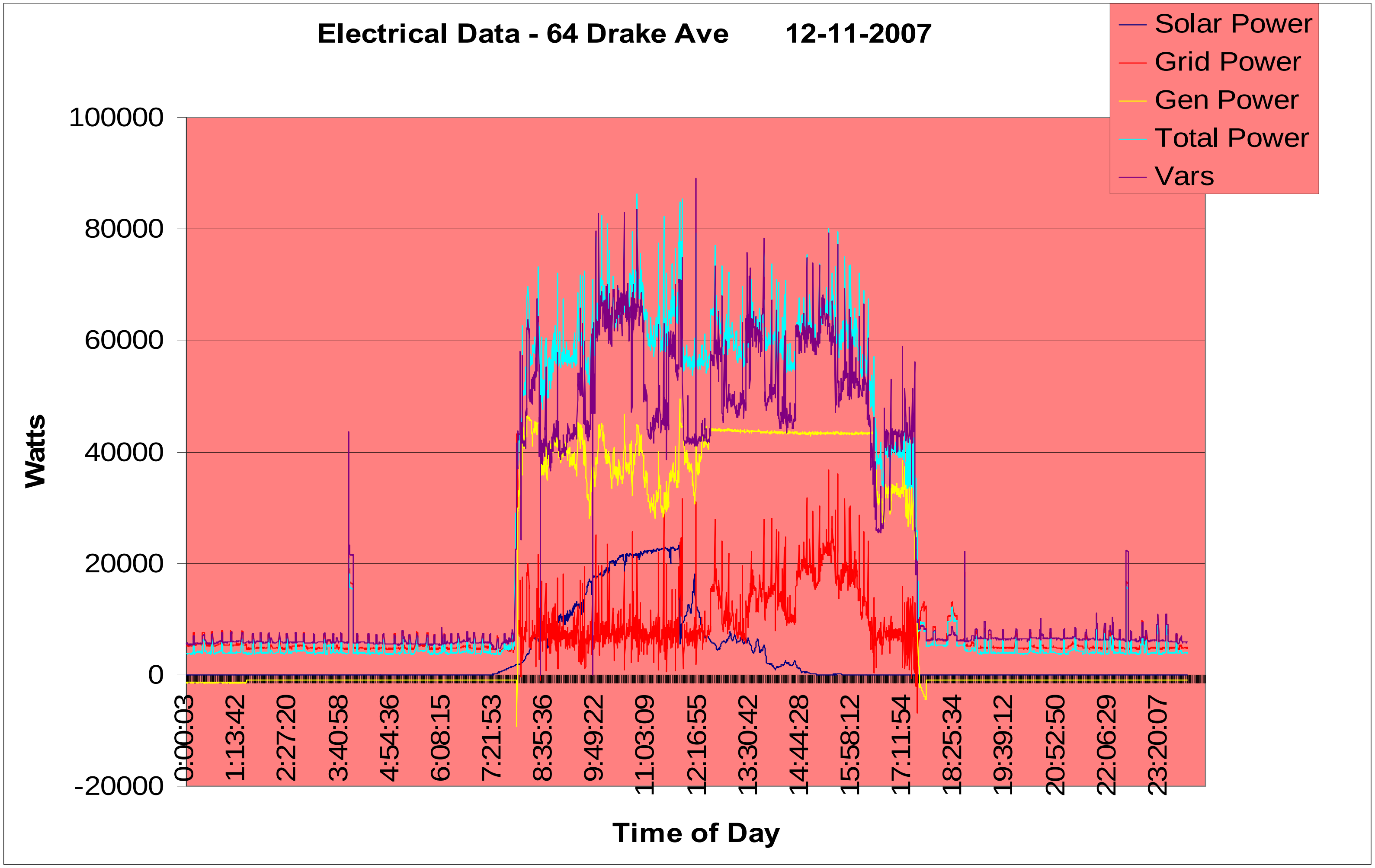


Figure 2 - BEFORE IMPLEMENTATION OF REACTIVE POWER (KVAR) CORRECTION (KVAR's shown in Purple)

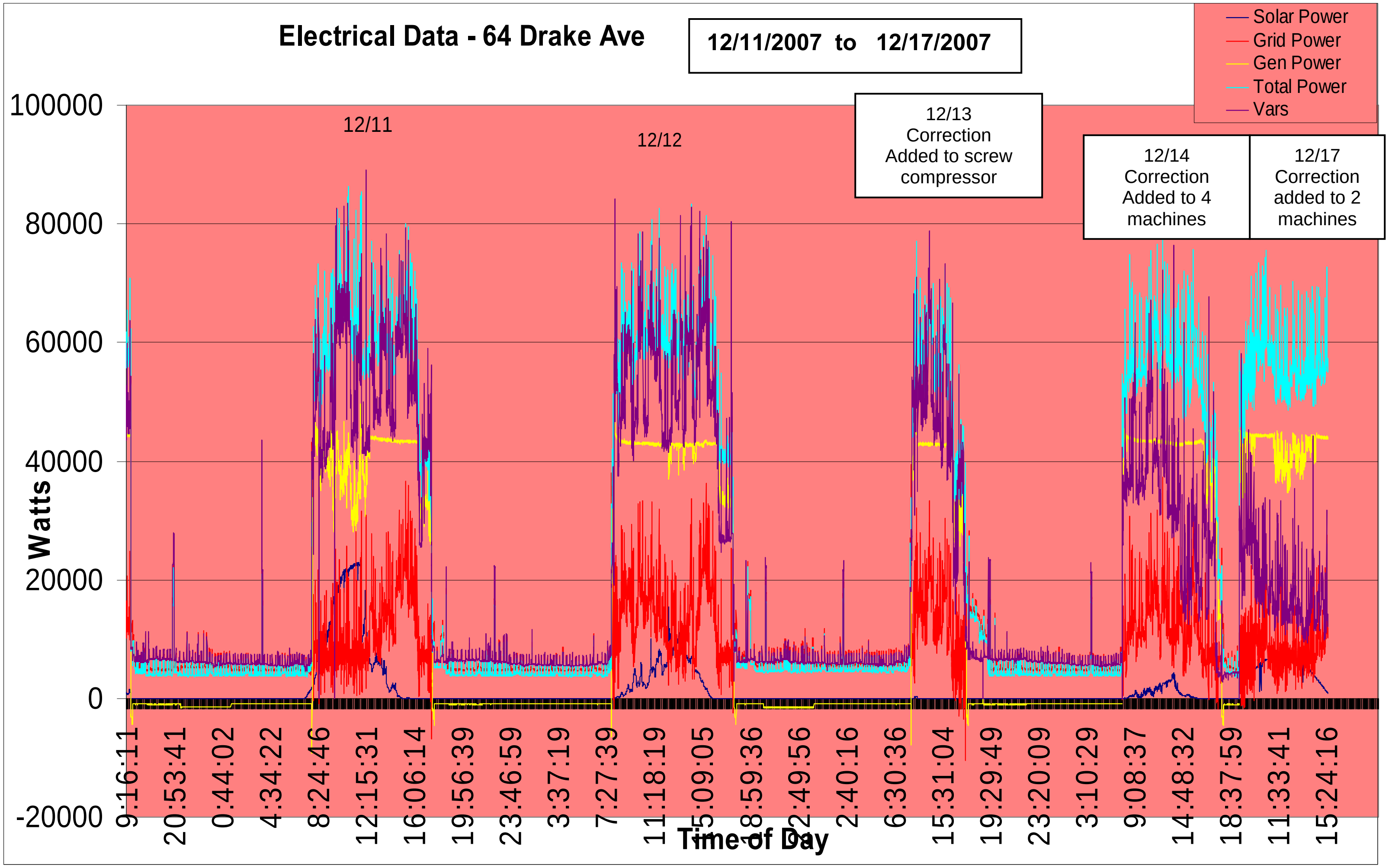


Figure 3 - DURING IMPLEMENTATION OF REACTIVE POWER (KVAR) CORRECTION (KVAR's shown in Purple)

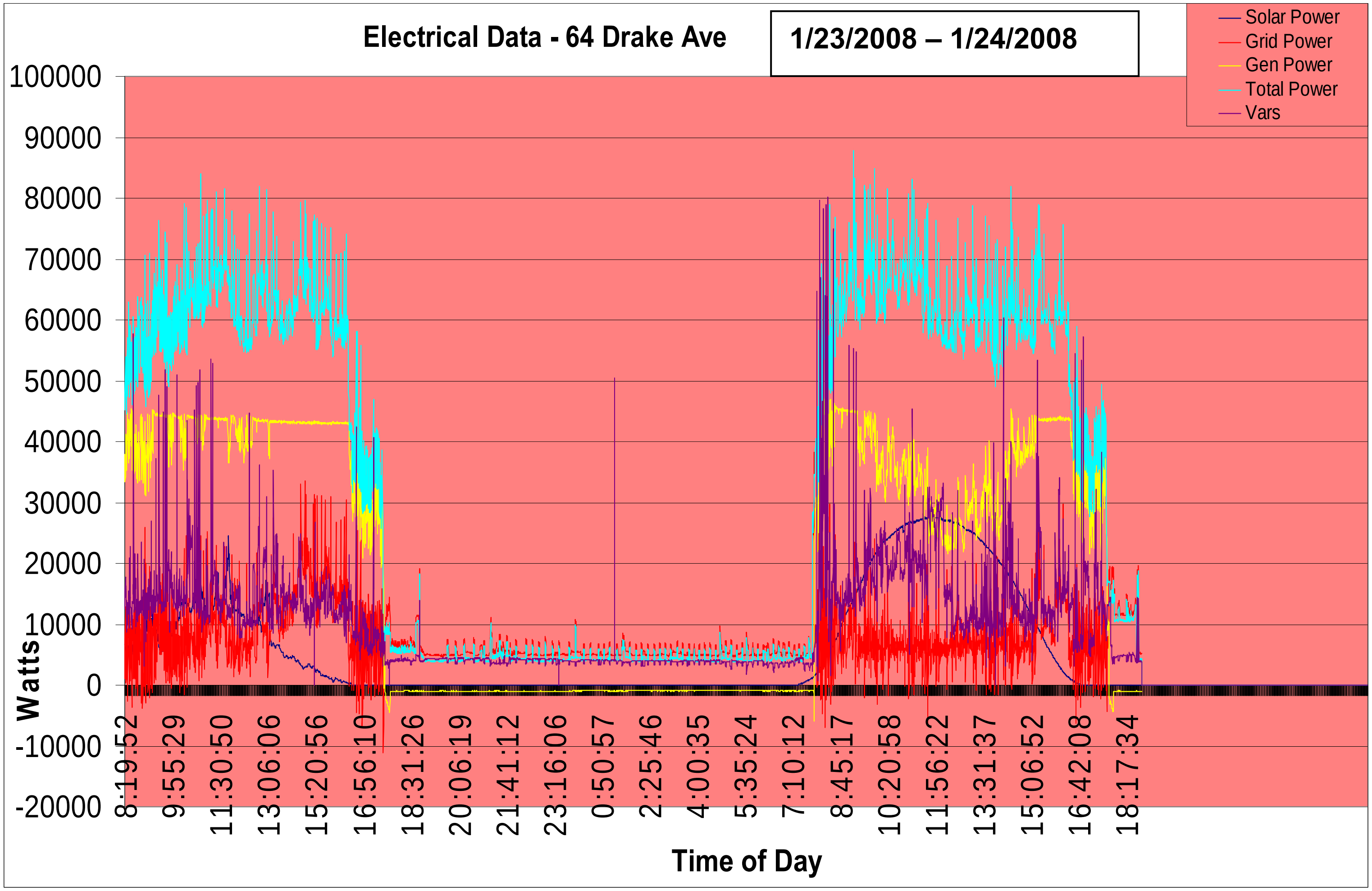


Figure 4 - AFTER IMPLEMENTATION OF REACTIVE POWER (KVAR) CORRECTION (KVAR's shown in Purple)

Figure 5 – The power monitoring System in the electrical room at Allied Converters

Figure 6 – Inverters for the solar array

Figure 7 – CHP System   Micro turbines are in the foreground. The heat exchanger is the cabinet to the rear and center of the two micro-turbines. The two tall, gray cabinets to the rear left are 10 ton absorption chillers that use the hot water from the heat exchanger to generate 43 degree chilled water during the cooling season.

EQUIPMENT ROOM

Figure 8 – Main Utility Circuit Breaker (left) and 1600 Ampere transfer switch (right). Automatically disconnects the internal service from the utility during a power failure.

Figure 9 – Protective relays for the CHP system

Figure 10 – 45 KVAR power factor correction at the utility service entrance. These devices are connected to and disconnected from the service by the monitor shown in Figure 5. The solar power meter is in the foreground on the far right

Figure 11 – 7.5 KVAR power factor correction at a load. The enclosure on the left is the PF correction. The enclosure measures 15” high x 8” wide x 6” deep. The device cost less than $ 700.

Figure 12 – 50 KW roof mounted solar array

Glossary of terms and abbreviations:

(Those marked with an "*" are copied from Wikipedia)

Ampere* Unit of measure of current. One ampere is approximately equivalent to $6.24150948 \times 10^{18}$ elementary charges, such as electrons, moving past a boundary in one second.

AC* Alternating Current is an electrical current whose magnitude and direction vary cyclically, as opposed to direct current, whose direction remains constant. The usual waveform of an AC power circuit is a sine wave, as this results in the most efficient transmission of energy. In the United States, the frequency of oscillation is 60 Hertz or 60 cycles per second.

BTU* The British thermal unit is a unit of energy used in the United States, particularly in the power, steam generation, and heating and air conditioning industries

CHP Combined Heat and Cooling (Cogeneration). A fuel is burned to generate electricity and the waste heat is captured and used to heat water. The heated water is then used for premises heating by being passed directly through a fan coil during heating season. The hot water can also be used for domestic hot water, as well. During cooling season, the hot water is passed through an absorption chiller to generate cold water, which is then passed through the fan coil for premises cooling.

Capacitor* A capacitor is an electrical/electronic device that can store energy in the electric field between a pair of conductors (called "plates"). The process of storing energy in the capacitor is known as "charging", and involves electric charges of equal magnitude, but opposite polarity, building up on each plate.

DC* Direct current (DC or "continuous current") is the unidirectional flow of electric charge. Direct current is produced by such sources as batteries, thermocouples or solar cells.

DG* Distributed generation generates electricity from many small energy sources. It has also been called on-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy.

GW Gigawatt. One billion watts. See "KW" .

Inductor* An inductor is a passive electrical device employed in electrical circuits for its property of inductance. An inductor can take many forms. Inductance (measured in henries) is an effect which results from the magnetic field that forms around a current-carrying conductor. Electrical current through the conductor creates a magnetic flux proportional to the current. A change in this current creates a change in magnetic flux that, in turn, generates an electromotive force (emf) that acts to oppose this change in current. Inductance is a measure of the generated emf for a unit change in current.

KVAR One thousand VAR (See VAR)

KW* Kilowatt**.** The watt is equal to one joule of energy per second. A typical household incandescent light bulb uses electrical energy at a rate of 40 to 100 watts. A kilowatt equals 1000 watts.

MW Megawatt. One million Watts. See “KW”.

PF* The power factor of an AC electric power system is defined as the ratio of the real power to the apparent power, and is a number between 0 and 1 (frequently expressed as a percentage, e.g. .5 pf = 50% pf). Real power is the capacity of the circuit for performing work in a particular time. Apparent power is the product of the current and voltage of the circuit. Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power can be greater than the real power. Low-power-factor loads increase losses in a power distribution system and result in increased energy costs.

VAR Volt-Amp Reactive. A unit of measure of reactive power. Reactive power is caused by the presence of inductive loads, or switching power supplies, such as those found on desktop computers. It is a result of the current waveform being out of phase (lagging) the voltage waveform.

Volt* The volt is the unit of electric potential difference or electromotive force.