Adding a 100 kVAr capacitor would improve the power factor from 60% to 95%. It would lower the current draw from 201 Amps to 126 Amps. This is a reduction of 75 Amps.
What is the reduction in line losses, with 4/0 conductor, and a resistance of 0.05 OHMS per 1000 feet?

—-Line losses (kW) = I^2 x R
—-With power factor of 60%, line current is 201, kW = $(201)^2$ x (0.05)300/1000 = (40401) x (0.015) = 0.606
—-With power factor of 95%, line current is 126, kW = $(126)^2$ x (0.05)300/1000 = (15876) x (0.015) = 0.238
—-Savings in line losses = 0.606 – 0.238 = 0.368 kW
—- Assuming this motor runs 12 hrs/day x 5 days/week = 3120 hours/year
—-Annual savings @ $0.10/kWhr = 3120 x 0.368 x $0.1 = $115/year
—-As a function of the total motor load = 0.368/100 = 0.368 percent

These numbers are an example only; each site is unique.

How would the voltage improve at the motor terminals, for a three-phase motor?

Voltage drop (V_D) = (1.732 x K x I x D) / CM

Where:

K = Direct-current constant. K represents the DC resistance for a 1,000-circular mils conductor that is 1,000 feet long, at an operating temperature of 75 degrees C. K is 12.9 OHMS for copper and 21.2 OHMS for aluminum.

Q = Alternating-Current Adjustment Factor: For AC circuits with conductors 2/0 AWG and larger, you must adjust the DC resistance constant K for the effects of self-induction (eddy currents). Calculate the "Q" Adjustment Factor by dividing the AC OHMS-to-neutral impedance listed in Chapter 9, Table 9 by the DC resistance listed in Chapter 9, Table 8. (in the National Electric Code (NEC))

I = Amperes: The load in amperes at 100% (not at 125% for motors or continuous loads).

D = Distance: The distance the load is from the power supply. When calculating conductor distance, use the distance between the load and power supply plus add in any up or down distance.

CM = Circular-Mils: The circular mils of the circuit conductor as listed in NEC Chapter 9, Table 8.

Applying the 3-phase formula, where:

K = 12.9 OHMS, copper
I = 201 A before and 126 A after.
D = 300 feet
CM = 211600 (Chapter 9, table 8)

V_D = before (1.732 x 12.9 x 201 A x 300 ft.) / 211600 CM = 6.367
V_D = after (1.732 x 12.9 x 126 A x 300 ft.) / 211600 CM = 3.991
V_D improvement = 6.367 – 3.991 = 2.376 V at motor terminals
There is also a voltage rise at the transformer.

Note: The NEC generally does not require you to size conductors to accommodate voltage drop. It merely recommends that you adjust for it when sizing conductors for load current. By performing voltage drop calculations, you are addressing system performance and efficiency issues.

How would the power factor adjustment in the utility bill change?

— kVArs would reduce from 133 to 33 = 100 kVAr per hour of operation.

—100 kVArs x 3120 hours per year = 312000 reactive kVAh

—1000 kW industrial customer above with 6,000,000kWhrs per year

—The annual reactive kVAh would be reduced from 6126000 to 5814000 kVAh

Using the billing formula for power factor, it would improve from 70 to 71.8.

71.8 – 70 ► 1.8 x 0.06% ► 0.108% x $450,000 = $486.00 per year

—Total savings utility power factor adjustment	$486.00
—Line loss savings	115.00
—Total	$601.00

Cost to install the 100 kVAr capacitor at motor control	$3,855.00

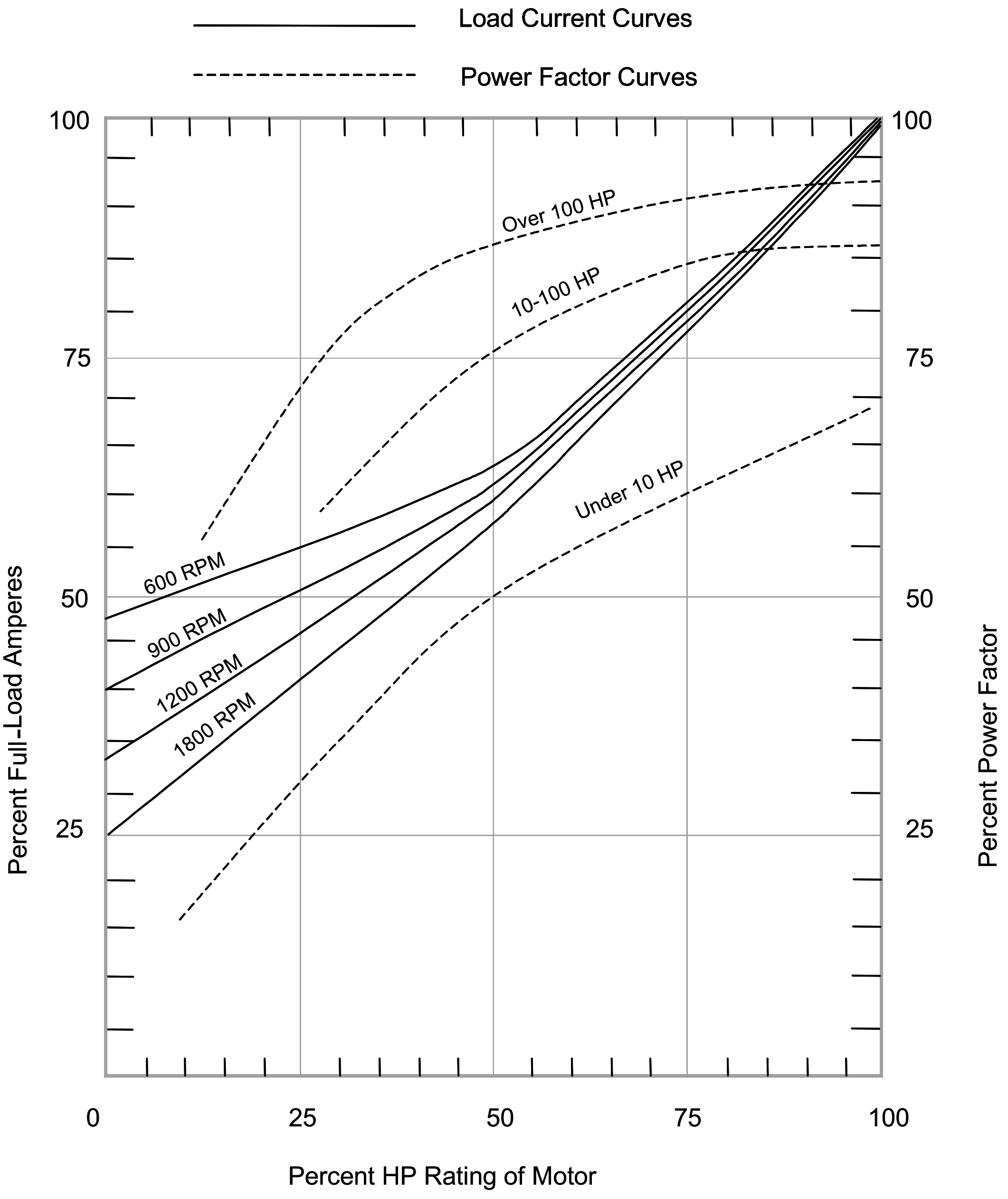
Simple payback = 6.4 years.

The estimated material cost alone is $2,855.00. Installation cost of $1,000 may not cover required additional equipment.

If this same capacitor could be installed at a motor control center (MCC) with multiple motors that operated more hours, the savings would increase, but so would the installation cost. When capacitors are connected to a bus, feeder or motor control center, a disconnect switch and over-current protection must be provided. Every site requires a unique configuration and savings calculations.

In the above example for a single motor installation, it is assumed that the capacitor will be installed between the motor circuit breaker and the starter contactor of the motor starter. If you wanted to install the capacitor on the motor terminals, you would be limited to 30 kVArs to prevent causing damage to the motor windings. Refer to vendor information for more details. Keep in mind that installing the capacitor on the line side of the motor contactors is the same as installing it upstream at the MCC, because it will be connected to the MCC bus even when the individual motor contactor is open. Make sure the MCC bus can handle the100 kVArs.

Power Factor and Load Current Curves



Typical load curves for 600 Rpm, 900 Rpm, 1200 Rpm and 1800 Rpm induction motors and typical power factor curves for the three-phase, general purpose induction motors.

Typical Motor Power Factor

When looking for the culprits that are dragging down the power factor, the easiest targets will be smaller lightly loaded motors. Large motors over 100 HP will have much better power factors but if they run many hours then you could take the total kilovars solution approach. You should always use the nameplate or measured data when possible rather than assume an average value. There are large motors that are not as efficient as the figure above would imply. The figure above is an interesting study.

Harmonic Distortion Concerns

All the above has assumed that there is no harmonic problem. If a facility has more than 15% non-linear load, such as adjustable speed drives, then a harmonic study should be performed before applying capacitors. The application of shunt capacitors can change the system response to injected harmonic currents. If a resonance condition occurs near one of the injected harmonic components, significant harmonic voltage distortion can result; causing transformer and motor overheating, capacitor fuse blowing, relay misoperation, and problems with electronic controls. An initial check of the resonant frequency can be made using the following formula:

$$H_r = [(kVA_{sc}/kVAr_{cap})]^{1/2}$$

Where: H_r = resonant harmonic (should not be close to the 3rd, 5th or 7th)

KVA_{sc} = the short circuit kVA at the capacitor location

$kVAr_{cap}$ = the capacitor kVAr rating

If the resonance occurs near a problem frequency, further analysis is warranted. Harmonic distortion problems can be avoided by designing harmonic filters as part of the shunt capacitor installation. The filters provide low impedance paths for the harmonic currents, preventing voltage distortion problems. It is important to include the possible increased duty requirements resulting from ambient harmonic levels when specifying filter component ratings. There is a new IEEE standard--*1531-2003 Guide for Application and Specification of Harmonic Filters*--that addresses these concerns.

Transient Overvoltage Concerns

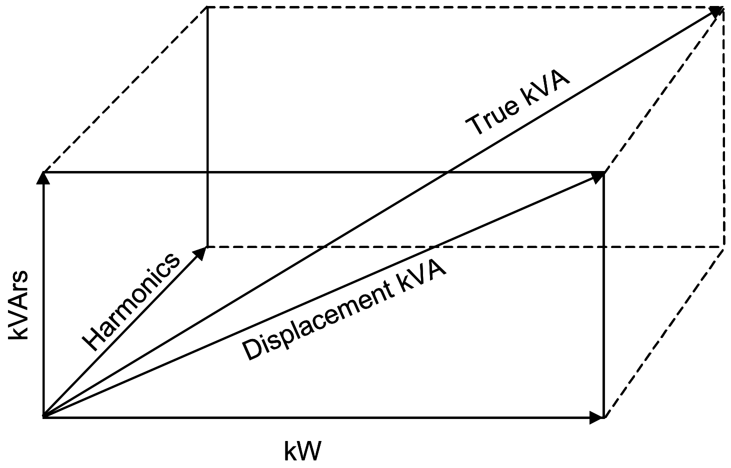
Transient overvoltages are always a concern when capacitor switching is involved. This concern can be addressed by the capacitor and/or filter vendor by using current limiting reactors. If the utility is switching capacitors on the distribution, then this transient must be included in the transient study. Further steps may be required, such as high-energy MOV arresters in addition to the reactors.

Adjustable Speed Drive and Harmonics

The rectifier front-end of adjustable speed drives converts AC to DC. This conversion process uses power electronic switches such as thyristors or transistors. This electrical switching process is fairly efficient if measured in kilowatts, but not so efficient if we measure in true RMS volt-amperes. There are many topology options for motor drives to reduce harmonics to tolerable levels. The worst may be as high as 75% total harmonic distortion (current) (THDi) to the best under 5% THDi. To reduce the current distortion to the minimum will probably double the cost. Obviously, customers and vendors will try to tolerate the harmonics unless the engineering design or operating problems after installation become apparent. Many vendors have developed harmonic modeling software programs to try to anticipate problems during the design stage.

New IEEE Standard for Calculating Power Components

Earlier we discussed the equation for calculating watts with no harmonics. The equation for Real Power (P) when harmonics are present adds another term, distortion (D) or harmonic (H). It turns out that harmonics do not contribute very much to real power, but they are a significant factor in measuring or calculating apparent power. Apparent power (S) and its components Real Power and Reactive Power (Q) are the actual quantities that define the rate of flow of the electromagnetic field energy we call electrical power. We can no longer simply talk in terms of watts. Fundamental apparent power is simply $S^2 = P^2 + Q^2$. When harmonic distortion is present you must add another term D, for distortion. The equation becomes $S^2 = P^2 + Q^2 + D^2$. D is measured in units of volt-amperes. For a complete explanation of this new concept, refer to IEEE Standard 1459-2000, referenced at the end of this note.



When kW, kVAr and harmonics are plotted in a Cartesian coordinate system, a three-dimensional box results, for illustration only.

The purpose of the above illustration is to emphasize that when harmonics are present, the true kVA is greater than the displacement kVA (60 Hz only). The issue is that the distribution system in question must be sized for the full RMS current. Not all measurement tools are capable of measuring true RMS values. According to the new IEEE standard 1459-2000, there are no power monitors that truly measure the full power spectrum. Since the working group completed it's work, there is one manufacturer that we are aware of that has incorporated the correct equations from standard 1459 for calculating kVA into two models but not all. Using the correct equations for calculating kVA is very important when considering if a transformer is overloaded when harmonics are present. The NEC takes this into account by requiring all electrical distribution systems must be capable of handling the full RMS current.

Single Phase Harmonics

Up to this point, we have discussed three-phase motor power factor correction and some issues if other three-phase non-linear loads are present. Now let us discuss harmonics from single-phase loads. In the opening paragraph, we discussed the rapidly growing segment of single-phase office equipment and electronic loads that use non-linear power supplies that can contribute significant harmonic currents into a premise wiring system. This can be in typical office buildings and in electronics manufacturing. Until recently, there were three mitigation measures typically taken to combat these single-phase harmonics. The first one was to use K-rated three-phase transformers designed for high harmonics; the second one was to double the size of the neutral in three-phase circuits; and the third one was to use a three-phase zigzag transformer. These measures increase the capacity of the distribution system to handle unwanted harmonic currents but do not reduce them. The NEC addresses the issue of harmonics by simply stating that the electrical contractor must provide conductors and switchgear of sufficient size for the total RMS current. This strategy provides for safe operation but ignores potential sizeable line losses and over-sizing of transformers. This is an inefficient strategy for users of electrical equipment as larger capacities equate to larger capital and operating costs.

Listed with the vendors at the end of this note are two companies that provide solutions to reduce the harmonic problem for concentrated single-phase loads. The principal harmonic generated by single-phase loads is the third harmonic (180 Hz) with some fifth harmonic (300 Hz). For a detailed explanation of harmonics see our Power Note on *Harmonics*. One of these products uses a patented scheme to block the third harmonic currents and the other product uses a more traditional harmonic filter scheme. The advantage of the third harmonic blocking is that it blocks third harmonic current from the distribution circuit, instead of providing it with a tuned filter. Blocking the third harmonic permits sizing the transformer for the nameplate wattage, ignoring the third harmonic load. It can also save up to 8% in energy use caused by line losses. The 8% energy savings comes from testing and modeling (see *Reference No. 4* at the end). The savings potential varies considerably in every facility due to the level of harmonic currents and the impedance of the circuits involved. There is no need to oversize the neutrals. *Harmonics Limited* is the manufacturer of the third harmonic blocking filter. *Powersmiths* is the manufacturer of the traditional harmonic filter scheme.

The ideal solution would be to have a standard limit on harmonic current in each electrical machine/appliance. Manufacturers have generally opposed efforts to create harmonic limit standards for individual loads. The manufacturers' argument is that taken alone, the harmonics caused by a single desktop computer is minimal. This is true. They contend that no one has proven any negative economic impact due to their non-linear power supplies. This is a point of disagreement. The IEEE paper on *Costs and Benefits of Harmonic Current Reduction* has a thorough explanation of the impact of harmonics. The result is that the building/facility owner must either waste capacity in the electrical distribution system or install harmonic mitigation measures at his expense. In the paper, the example illustrates a potential savings of 8% by mitigating the harmonics.   When the percent of non-linear load is below 10%, there is generally not much concern, but if it grows to beyond 30%, then you should begin to be concerned.

Typical Modern Office Building Distribution System

In a typical modern office building, the service voltage from the utility is usually 277/480 V, three-phase. Motor loads, such as the ventilation fans, chillers and elevators run on 480 V three-phase. Some of these loads may have non-linear adjustable speed drives. These loads have not yet proven to be a problem.

The lighting load, while it is single-phase 277 V, is generally fed from a dedicated three-phase panel at 277/480 V. This entire lighting load is non-linear. The current harmonic distortion ranges from 20% to 30%. Fluorescent lighting has been the norm for over 50 years and is not a problem because the electricians don’t use shared neutrals in the individual lighting circuits. You could make an argument to block the third harmonic currents from the dedicated lighting panel back to the service entrance panel. This is not a common application in our PG&E service territory, but is a good idea to reduce losses on the common neutral.

The remaining loads are the office receptacle loads such as computers, copiers, fax machines and printers. Most, if not all of this load is non-linear with very high harmonic current. The voltage is 120/208 V and is stepped down from a three-phase feeder with a transformer owned by the facility. It is these non-linear single-phase loads that the two vendors above are suggesting their particular mitigation solutions be applied.

There are vendors that manufacture small harmonic filters, but this market has not done well because of the lack of knowledge on the part of the users. Making a harmonic filter for office equipment is relatively easy because the harmonic current is predominately the third harmonic. It is sufficient to either block or provide the third harmonic. The traditional harmonic filter using simple LC components is tuned to provide the third harmonic frequency current.

Three-Phase Harmonics

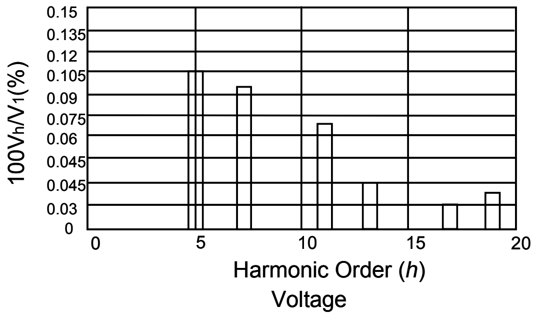
The philosophy discussed about power factor correction for three-phase motors is very similar to the philosophy to correct harmonic currents. Both the vars for motors and harmonic currents for non-linear office machines are wasted energy in the distribution system. The system must be sized for these extra currents. Or we can provide vars at the motor to maximize the distribution system capacity.

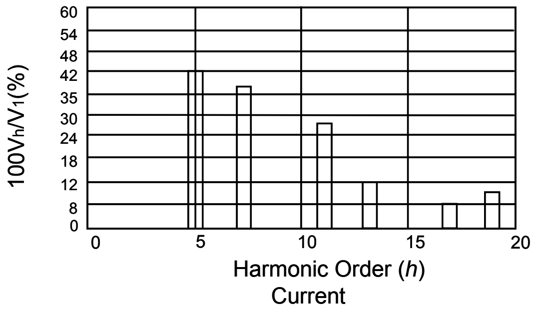
In the case of the non-linear office equipment, we could install small harmonic filters at each load or take the systems approach recommended by the two manufacturers mentioned above—*Harmonics Ltd.* and *Powersmiths*.

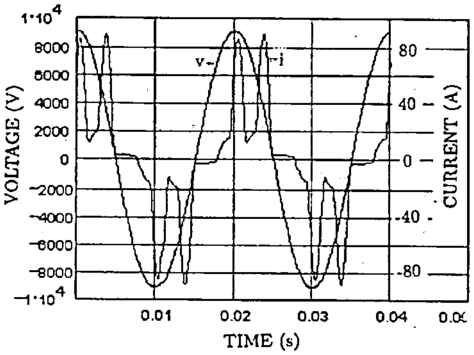
Example in Industrial Plant

In a real example, an industrial facility’s major load consists of non-linear AC/DC converters. As a test to evaluate harmonic measurement techniques, the plant temporarily disconnected the harmonic filters to generate the following values, taken on the primary side of the service transformer. The figures below use the voltage and current waveshapes and harmonic spectrum.

True RMS	60 Hz	Harmonics
P = 653.78 kW	P = 653.78 kW	
S = 993.08 kVA	S = 806.52 kVA	D = 579.4 kVA
	Q = 472 kVA	
Power factor = 65.8	Power factor = 81.1	







The fundamental apparent power (806 kVA) and the fundamental reactive power (472 var) indicate the value of the fundamental power factor correction capacitors to overcome the effects of relatively large firing angles used in natural commutated phase control converters. This reactive power can be corrected by means of static capacitors used in passive filter configuration. The better solution is to use an adjustable speed drive with the input power factor corrected to 95% and a maximum of 5% current harmonic. This can be achieved with input rectifiers that use 18 and 24 pulse topologies instead of the routine six-pulse type. They are more expensive but you save the cost of the harmonic filter and never have to worry about filter failure or changing harmonic conditions. This topology is becoming more common in drivers over 500 HP and very common in medium voltage applications.

The difference between the true RMS VA and the 60 Hz VA, 993.08 – 806.56 = 186.56 kVA, is a potential 23.1% under measurement with metering designed for 60 Hz measurement only. **A significant danger can be if you simply measure the 60 Hz power with traditional metering and calculate the apparent power to determine if a supply transformer is adequately sized, then you would in this example potentially overload the transformer.** The demand profile can also have an effect. According to the new IEEE standard—1459-2000, the working group was not aware of any power monitors capable of making this measurement. We now know of one manufacturer that has two models that use the correct equation for calculating kVA in the presence of harmonics and unbalanced loads.

However, if you can accurately measure the harmonics, you can calculate the correct value for apparent power with the new formula. In addition to the added influence of harmonics, unbalance contributes to the calculation of kVA loading. Voltage and current unbalance are included in the new equations for kVA in IEEE Standard 1459-2000.

IEEE has a standard—C57.110-1998, *Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents*—which provides methods to conservatively evaluate the feasibility of supplying additional nonsinusoidal load currents. The standard provides calculations to derate a transformer given a specified load current with specified harmonic spectrum. The PG&E internal standard recommends using this evaluation method when the total current harmonic distortion exceeds 15%.

Measurements

When assessing the potential savings for mitigating power factor and/or harmonics, it is imperative to measure all the energy parameters using an instrument capable of measuring true RMS values and making accurate calculations of watts, vars, volt-amperes, and harmonics. It could be dramatically misleading to simply measure the current before and after and assume an energy savings without also measuring the watts. The revenue meter measures watts. Also, it is important to remember that trying to measure efficiency in the field is impossible if you cannot hold the load constant.

Definitions

Displacement Power Factor is the power factor measuring only the 60 Hz angular displacement between the current and the voltage. Power factor correction capacitors can reduce this angular displacement. This measurement can be misleading if harmonics are present.

True Power Factor is properly defined as the real power divided by the apparent power. This measurement includes all frequencies, not just the 60 Hz. The challenge is to measure the true RMS VA with all the harmonics. Capacitors cannot correct poor power factor due to harmonics except as a component of a LC filter.

RMS, root mean square is a mathematical term for measuring voltage or current properly. The assumption is that the measuring instrument is sampling continuously, many times per cycle, preferably more than 64 times per cycle. Mathematically, you square the values, take the mean of the squares, and then take the square root of the mean.

The RMS method of measuring AC current accurately measures the heating effect of AC current through a resistor (wire). It is very important to know this value accurately to properly size conductors, transformers and capacitors. To measure harmonics, a high sampling rate is required, generally 128 times per cycle and more. Many measurement tools use peak sensing or averaging techniques and then multiply that value times a set multiplier to get to the RMS value. This can be very misleading when the waveshape is distorted. PG&E's Power Quality Consulting (PQC) has a reference paper that explains this problem. For a copy of this reference paper, please send us an email at *mailto:PowerQualityWeb.*

Harmonics. Ideally, voltage and current waveforms are perfect sinusoids. However, because of the increased popularity of electronic and other non-linear loads, these waveforms quite often become distorted. This deviation from a perfect sine wave can be represented by harmonics—sinusoidal components having a frequency that is an integral multiple of the fundamental frequency. Thus, a pure voltage or current sine wave has no distortion and no harmonics, and a non-sinusoidal wave has distortion and harmonics. To quantify the distortion, the term total harmonic distortion (THD) is used. The term expresses the distortion as a percentage of the fundamental (pure sine) of voltage and current waveforms. See PQC's power note on *Harmonics* for more information.

Unfortunately, there is a new term we will have to learn about in the future--inter-harmonics. The present generation of power monitors only measures integral harmonics, not the harmonic currents in between each integral multiple of 60 Hz. These can create further wasted energy. We can measure the total true RMS current and properly size equipment based on the current, but the present generation of power monitors will not show this new inter-harmonic component.

EPS, Energy Procurement Surcharge. Hopefully, this is a temporary charge that will expire when the wholesale power crisis ends. The surcharge under this schedule provides an increase in revenues, subject to refund or adjustment, for the purpose of improving utility recovery of the costs of procuring future energy costs in the wholesale market. The surcharge varies from 1 cent to over 10 cents per kWh depending on the rate schedule and time of use.

References

1. Electrical Transmission and Distribution Reference Book, 4th edition, 1950, Westinghouse Electric Corporation, chapter 8, Application of Capacitors to Power Systems.
2. IEEE Standard 1531-2003 Guide for Application and Specification of Harmonic Filters.
3. IEEE Standard 1459-2000 Trial Use Standard for Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Non-Sinusoidal, Balanced, or Unbalanced Conditions.
4. IEEE/IAS Costs and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Office Building, IEEE Transactions on Industry Applications, Vol.32, No.5, September/October 1996.
5. IEEE Standard 141-1993, Recommended Practice for Electrical Power Distribution for Industrial Plants. Chapter 8, Power Factor and Chapter 9, Harmonics in power systems. This publication is also known as the Red Book.
6. IEEE Standard C57.110-1998, Recommended Practice for Establishing Transformer Capability When Supplying Nonsinusoidal Load Currents.
7. R.C. Dugan, M.F. McGranaghan, S. Santoso, and H. W. Beaty, *Electrical Power Systems Quality*, Second Edition, McGraw-Hill, Professional Engineering Series, New York, 2003.

Vendors:

Myron Zucker, Inc. 315 East Parent Street, Royal Oak, Michigan 48067-3728.
Tel: (248)-543-2277 Website: www.myronzuckerinc.com

Trans-Coil, Inc., 7878 North 86th Street, Milwaukee, WI 53274.
Tel: (414) 357-4480 Website: www.transcoil.com

EATON/Cutler-Hammer. Engineering Services and Systems.
Tel: 1.800.809.2772 Website: www.Eaton.com

Square D, a division of Schneider Electric. Power Management Products.
Tel: 888-778-2733 Website: www.squared.com

GE/Ultravar Capacitors and Controls, 381 Broadway, Fort Edward, NY 12828-1000.
Tel: (518)-746-5229.

ABB and Services/Auto Capacitor Banks Website: www.abb.com
European IEC voltage (400v) and frequency (50Hz) ratings only?

Harmonics Limited, 32 Pico Street, San Rafael, CA 94903.
Phone: 877-437-3688 Website: www.harmonicslimited.com

Powersmiths International Corp., 10 Devon Road, Brampton, Ontario, L6T 5B5, Canada.
Phone: 1-800-747-9627 Website: www.powersmiths.com

Dranetz-BMI, Edison, New Jersey. Only known manufacturer of power monitors that use the IEEE Standard 1459 to evaluate distortion and unbalanced loads.
www.dranetz-bmi.com

Consultants:

Electrotek Concepts, Inc., 408 North Cedar Bluff Road, Suite 500,
Knoxville, TN 37923-3605.
Tel: 865-470-9222. Website: www.electrotek.com