**Pacific Gas and
Electric Company**

Economics of Power Factor Correction in Large Facilities, >400kW

Electric Power Basics

Electrical power in an Alternating Current (AC) circuit has three components: real power, reactive power and apparent power. The component we are most familiar with is called real power measured in watts (W), or more typically kilowatts (kW). Real power is considered to be the work-producing component. Another component is reactive power measured in volt-amperes-reactive (var). Reactive power is not used to do work, but is needed within an electrical system to operate equipment such as motors, transformers and power electronics. Apparent power is comprised of both real and reactive power and is measured in units of volt-amperes (VA). All electrical equipment is rated in apparent power, volt-amps, because it must handle the full Root Mean Square (RMS) current. The full RMS current if measured with a capable measuring tool will include the 60 Hz components and all the harmonic components. See definitions for *RMS* and *Harmonics* at the end of this publication.

Power factor is a ratio of the amount of real power to apparent power, and represents how much real power electrical equipment utilizes. Power factor only exists in AC circuits, not Direct Current (DC). See *Definitions* section at the end.

A power factor of any value other than unity is caused by inductive or capacitive reactance and harmonics in the circuit. If an AC circuit only has resistive, linear loads, then the power factor is unity. Most loads connected to electrical distribution systems are inductive. A new load that is growing in importance is rectifier front end for power electronics and drives. This load can have a very high displacement power factor but a poor true power factor due to the harmonic distortion.

About 60% of electrical load today is comprised of motors. Motors, along with transformers and lighting ballasts, use electromagnetic fields to operate. Electromagnetic fields cause inductive reactance. This inductive reactance has two effects. First, it causes the current to lag the voltage; this can be measured as an angular displacement between 0 and 90 degrees, and second, it affects the resistance.

To illustrate the above relationships, we can use a right triangle, some trigonometric functions and algebra.
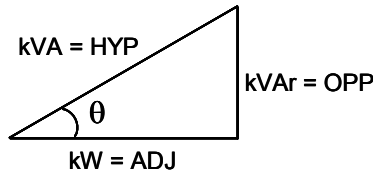
      Power factor = Real Power (W)/Apparent Power (VA)

This is true power factor because it includes the total RMS current.

      Three phase watts = $\sqrt{3}$ x Voltage (V) x Current (A) x Power Factor

Assuming there are no harmonics, power factor can also be equal to the Cos θ (theta), the displacement angle between the voltage and the current of each phase. The cosine theta function is the displacement power factor and is true only for 60 Hz power, because the kW component is 60 Hz only, the fundamental frequency. This displacement ratio is the power factor as indicated in metering by watt-hour and var-hour meters, again assuming that the AC voltages are sinusoidal.

Cos θ = kW/kVA = adjacent/hypotenuse

kVA = HYP

kVAr = OPP

θ

kW = ADJ

True power factor is the ratio of the real (working) power to the apparent power. True power factor includes all frequencies, not just 60 Hz. A high power factor would be close to unity whereas a low power factor would be below 60%. Do not assume that 60% has any magical meaning. As electrical equipment needs to be sized to handle the apparent power, it is desirable to have a high power factor to keep losses to a minimum and allow for the use of the smallest size conductors, transformers, and other electrical distribution system equipment to meet load requirements.

For example, an industrial facility is operating with an average 1000 kW demand and the apparent power is 1250 kVA. The power factor is 1000/1250 = 0.8 or 80%.

What is the PG&E Methodology for Power Factor Billing Adjustment?

For customers with peak demand <u>over 400 kW</u>, PG&E will install revenue metering capable of recording kilowatt demand, kilowatt-hours (kWh) and reactive kilovolt-amp hours (rkVAh). Interval meters can record these values every 15 minutes. For the power factor that is used in billing, the kilowatt-hours and the reactive kilovolt-amp hours are totaled for the month and a single calculation is performed to provide an average value for that billing period. The equation is:

Power factor = cos[arc tan(rkVAh/kWh)]

rkVAh

$$TAN\ \theta = \frac{rkVAh}{kWh}$$

θ

kWh
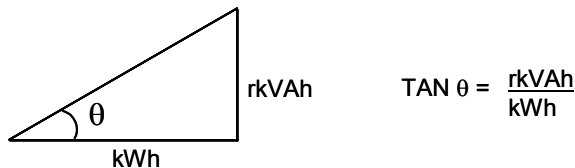
Trigonometric reminder: the tangent of an angle, when it is considered as part of a right triangle, is the ratio of opposite side to the adjacent side (as depicted in figure above). These are the two values that PG&E records, kWh (kilowatt-hours) and rkVAh (reactive kilovolt-amp hours). Arc tan is the function that determines the angle whose tangent is equal to a numerical value. Therefore, power factor can be calculated using the cosine function if we know the displacement angle (θ), for 60 Hz only.

This value is acceptable if we ignore non-linear, distorted currents, i.e., harmonics. Most utility revenue meters are designed to ignore all but linear, 60 Hz, power. If a kilovolt-amp value or power factor is calculated based on a utility revenue meter measuring kilowatt-hours, there is a potential error of up to 15%, positively or negatively, when harmonic loads are present. Fortunately, the kilowatt-hour reading is accurate well within utility standards. Harmonics will be discussed later.

It is important to remember that the <u>power factor calculated for the monthly billing is an average value for the whole month</u>. Since there can be large loads that cycle with different power factors within a premise, a power factor study should include these significant individual large loads with their individual operating hours (load profiles). Generally, it is most economic to address individual large loads for power factor correction close to the load, such as large compressors or machinery. In a power factor study, it is also necessary to identify any other capacitors within the facility and ask the utility about capacitor locations near the facility. The reason for ascertaining any utility capacitors nearby is because they contribute Vars and can be an issue that can affect any harmonic resonance. Be sure to include non-linear loads within the facility such as rectifiers, variable frequency drives, welders, etc, in the assessment. These sources of harmonics need to be accounted for when designing the capacitor correction by making the capacitor installation a combination var and harmonic filter. This will increase the cost but is absolutely necessary to prevent failure of the capacitors.

Why should we be concerned with **P**ower **F**actor?

Low power factor means lower operating efficiency which results in a need for larger conductors (wires), increased equipment capacity, more electrical losses and lower voltages. This could mean higher capital investment, higher expenses, and diminished performance.

Assume a 1000 kW load with a power factor of 70%. Why improve the power factor to 90%? Power factor should be improved to 90% because non-productive kVArs can be reduced from 1021 to 484 kVAr.

The kVA would be reduced from 1429 kVA to 1111 kVA. On a 480 V circuit, this is a reduction of 1718 – 1337 = 381 amps. This could free up (productive) capacity for new loads.
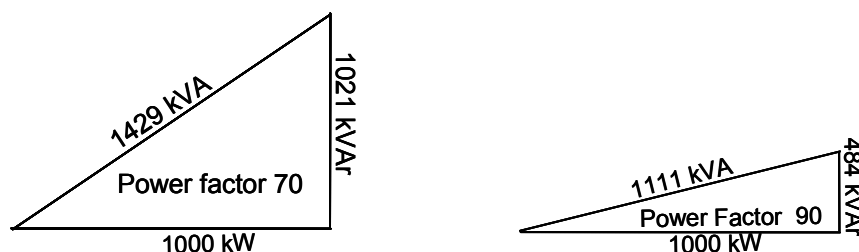
The **example calculation** below is for a PG&E customer to increase power factor from 70% to 90%. Values given are average for a year, not monthly or season specific.

PG&E does not calculate an annual billing. The example below is to illustrate a hypothetical annual estimate.

—Industrial customer with total annual kWh **=** 6,000,000
—Average billing demand 1000 kW; power factor **=** 70% (1000 kVArs): load factor 0.65
—Average kWh charge before Energy Procurement Surcharge (EPS)
    and taxes **=** $0.075
—Annual charge before EPS and taxes **=** $450,000
—Power factor adjustment is 0.06% or each percentage point below
    or above 85%. Below is a penalty, and above is a credit.
—Power factor adjustment for 70% = 85 –70 = 15 x 0.06 % = 0.9 % x 450,000 **=** $4050
—Power factor adjustment for 90% **=** 90 – 85 = 5 x 0.06% = 0.3% x 450,000 **=** $1350
—Power factor adjustment would change from a penalty of $4050 to a credit of $1350
    resulting in a net gain of $5400 per year.
—$5400 is 1.2% of $450,000 before adding EPS and other taxes. EPS is described in the
    Definitions at the end of this publication.

Keep in mind that this power factor adjustment only applies to customers that have a demand of more than 400 kW and PG&E has a rkVAh meter in place. For smaller customers there is no power factor adjustment. PG&E uses power factor correction capacitors on the distribution feeders to correct the power factor during peak load conditions to better than 98% going in to the substations. All the ratepayers subsidize this capital cost to minimize line losses for which all consumers benefit in lower rates by having a more energy-efficient electric system.

Southern California Edison (SCE) and San Diego Gas & Electric (SDGE) use a different approach from PG&E for power factor adjustments. They use revenue meters that record 15-minute interval values for kWh and rkVAh and save the maximum value for the month to calculate the power factor adjustment instead of totaling the values into a single sum for the month. Another difference is that the threshold to make a power factor adjustment to a bill is a lower kW demand than PG&E. The PG&E threshold is 400 kW. For SCE it is 200 kW and for SDGE it is 300 kW.

Other utilities may use higher penalties, based on a higher neutral point such as a power factor of 98 instead of 85. Some use kVA metering to charge for demand instead of kW. This is an incentive to improve power factor and reduce harmonics because kVA demand metering measures the total RMS current, not just the 60 Hz current used in kWh meters. Refer to page 11 where the new Institute of Electrical and Electronics Engineers (IEEE) standard on measuring power describes more about this topic.

Example Solution

The proposals below are for economic comparisons only. They are not meant to be an engineered solution. Consult with an experienced electrical contractor, electrical engineer, or contact one of the manufacturers listed below for design assistance.

The estimates below will be for two viable options, both stepped. One is pure capacitors and the second is a combination of capacitors and inductors to filter out harmonics. Any customer contemplating a power factor study must include existing and future harmonic content of the

loads in the premise because failure to do so will result in a potential catastrophic failure of the capacitors. The capacitors are designed to operate in steps because it is not recommended to size individual capacitor steps larger than 100 kVArs for 480 Volt (V) installations.

For 480 V industrial motors, capacitor steps larger than 100 kVArs result in high voltage transients that leads to motor insulation breakdown. Process loads can vary considerably during daily operation. You never want to switch on more vars than you need for bringing the power factor close to unity and also you don't want to boost the voltage too high when there is little demand for Vars. Some loads are sensitive to higher voltage above 127 V (on a 120 V base). This could cause nuisance tripping for over voltage or premature failure.

In the example above, the customer could use about 500 kVAr of capacitance. If these capacitors were installed at the service entrance as a multi-step bank, the approximate estimated material cost alone would be:

a) 500 kVAr, 10 step control, $21,405
b) 500 kVAr, 5 step control with 5th harmonic filter, $42,583
c) 500 kVAr, single capacitor, $14,930, not recommended. It is customary to install a stepped bank with individual capacitor units in 50 to 100 kVAr size.

If we assume the labor to install is at least $10,000 and no harmonic issues, the installed cost for option (a) would be $31,405. This will not reduce line losses within the facility. It will only save the utility penalty of $5400. The simple payback would be 31405/5400 = six years. The above price estimates do not include variables such as outdoor enclosure, relocation of existing panels, a disconnect switch, over-current protection or related electrical monitoring/controls.

Generally, there are two economic drivers that would cause a customer to consider installing power factor correction capacitors. The most common reason for our customers is that they want to add load but are constrained by the capacity of their distribution system. Sometimes it is more economical to install capacitors close to the load than it is to increase the distribution systems.

The second economic driver is to reduce the utility penalty for poor power factor. Because PG&E uses an average value for the month, this can allow the capacitor to be sized for providing a cumulative value for the month as opposed to a peak demand value.

Capacitors should be placed as near the load as possible or near the ends of feeders for three main reasons:

1. Losses are reduced in the circuits between the loads and the metering point, by reducing total current.

2. Voltage is raised near the loads, giving better motor performance. Reducing the current reduces voltage drop.

$$\text{Voltage drop} = V = IR \cos \Phi + IX \sin \Phi$$

Where:
V   is the voltage drop in circuit, line to neutral
I   is the current flowing in conductor
R   is the line resistance for one conductor, in OHMS
X   is the line reactance for one conductor, in OHMS
Φ is the angle whose cosine is the load power factor
$\cos \Phi$ is the load power factor, in decimals
$\sin \Phi$ is the load reactive factor, in decimals

Note: The voltage drop V obtained from this formula is the voltage drop in one conductor, one way, commonly called the line-to-neutral voltage drop. For single-phase circuits, multiply V by 2 and for three-phase circuits, multiply V by 1.732.
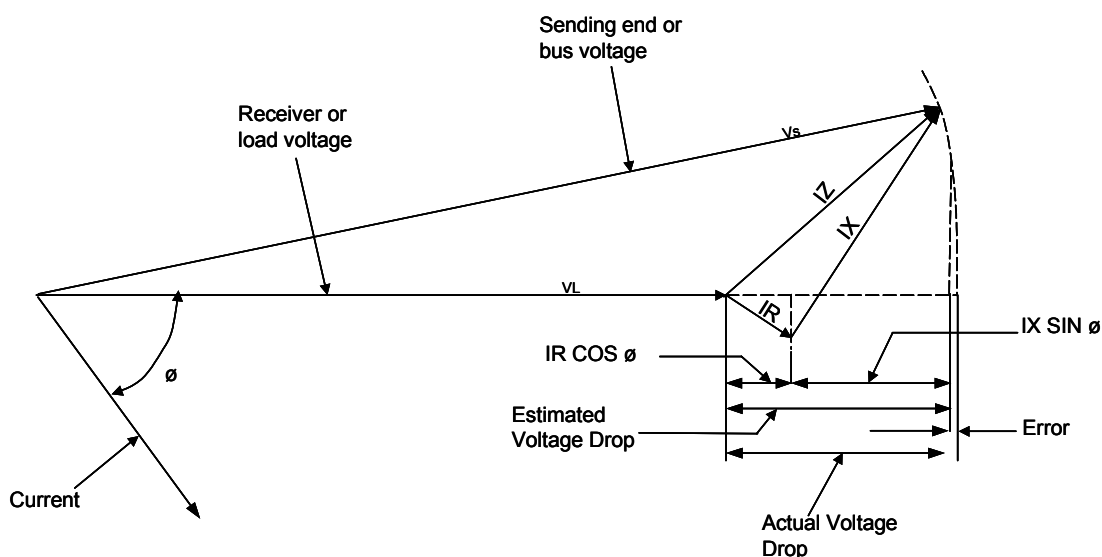
Phasor diagram of voltage relations for voltage-drop calculations

3. Capacitor kVAr can be reduced automatically as the load drops off by installing some of the capacitors directly on loads so they are switched off with the loads.

When there are many distributed smaller loads, then a compromise approach may be better. Let us look at an example where we have a single 100 kW air compressor in the facility that is 300 feet from the service entrance. Let's assume that the average uncorrected power factor is 60%. We will install a single 100-kVAr capacitor at the motor and switch it on with the motor. However, the capacitor must be connected before the motor starter contactors to prevent motor damage due to transients from switching the capacitor. Now we can also reduce line losses between the motor and the service entrance. The operating voltage is 480 V. The table below is to illustrate some variables as power factor changes. These variables include transformer size and wire size because of cost and space requirements.

kW	100	100	100	100	100
Power Factor	100%	90%	80%	70%	60%
kVAr	0	48	75	100	133
kVA	100	111	125	142	167
Load amperes	120	133.7	150.5	170	201
Transformer	100 kVA	125 kVA	125 kVA	150 kVA	200 kVA
NEC wire size	1/0	1/0	2/0	2/0	4/0
Wire diameter	0.375	0.375	0.419	0.419	0.528

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 <u>reduction in line losses</u>, with 4/0 conductor, and a resistance of 0.05 OHMS per 1000 feet?

–-Line losses (kW) **=** I² 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
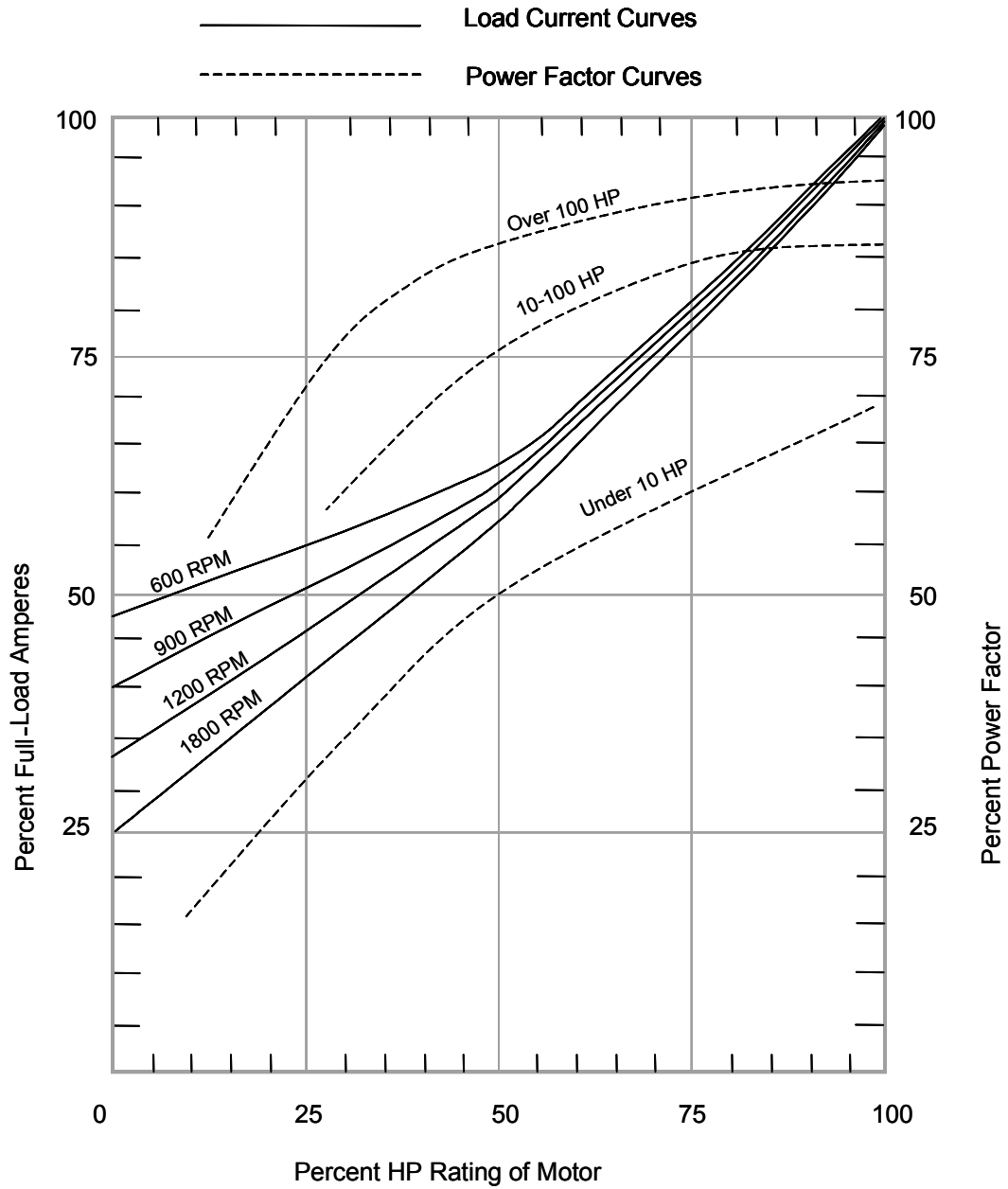
Simple payback = 6.4 years.

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

——————————— Load Current Curves

- - - - - - - - - - - Power Factor Curves

Percent Full-Load Amperes (vertical axis, left)

Percent Power Factor (vertical axis, right)

Percent HP Rating of Motor (horizontal axis)

Over 100 HP

10-100 HP

Under 10 HP

600 RPM

900 RPM

1200 RPM

1800 RPM

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.

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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:

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

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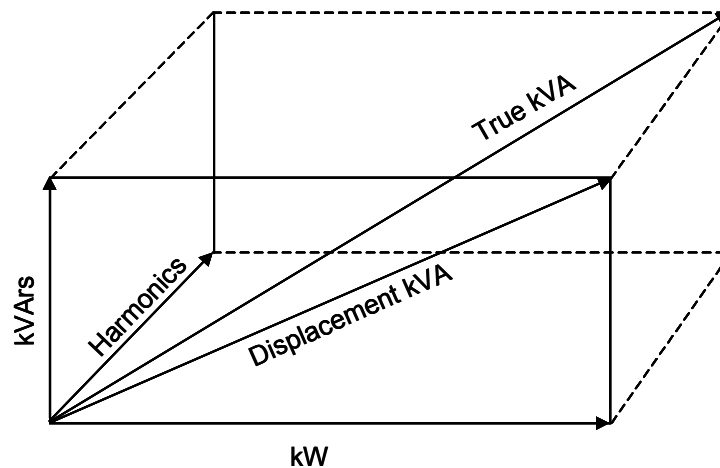
When kW, kVAr and harmonics are plotted in a Cartesian coordinate
system, a three-dimensional box results, for illustration only.

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	
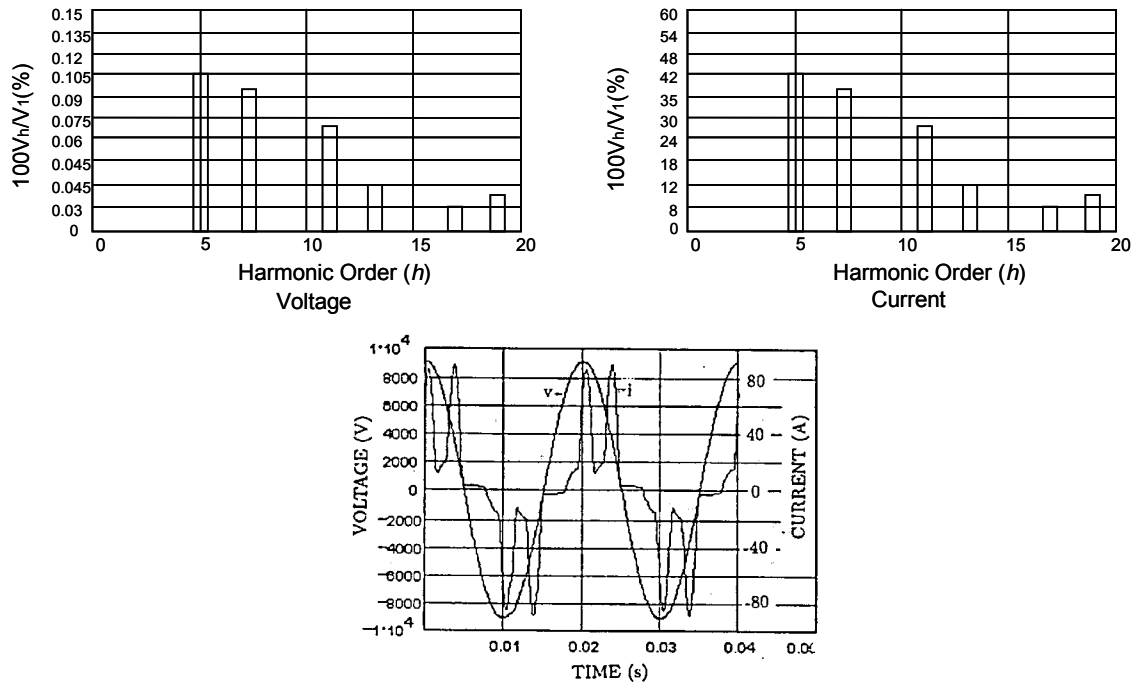
The fundamental apparent power (806 kVA) and the fundamental reactive power (472 var) indicate the value of the fundamental power factor correction capacitors to overcome the effects of relatively large firing angles used in natural commutated phase control converters. This reactive power can be corrected 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.

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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

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