Electric Power:
Industrial Billing Penalties and the Truth about Power Factor

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Introduction

Our current economic condition demands that we use less power or at least use it more efficiently. Many power companies attempt to ensure efficient use by fining what are considered inappropriate Power Factor measurements. **While the method of tracking Power Factor may be logical for general usage, it not always an effective measurement to use for industrial clients**. Because electrical power has both direction and magnitude, it is important to consider both the Power Factor and the load. Otherwise, companies that are actually using minimal amperage can be unfairly fined, especially those that are making strides to improve power efficiency and should be encouraged in their efforts. **Another consideration is the way the power companies measure peak consumption rates; in many cases, they are taking unfair measurement of spikes instead of averaging the consumption**. These billing practices need to be unveiled, examined and improved.

Electric power providers are always looking for ways to control cost and motivate consumers to conserve in meaningful ways. At first glance, conservation might be best done by simply reducing demand. One tool that utility companies have to control efficiency is a billing policy that includes fines for overconsumption or for what appears to be inefficient consumption. Implementing "appropriate" billing policies is difficult, however, and sometimes new efficiency technologies can create conflicts with policy. This paper explores some of the current billing/fining practices and makes suggestions for revising policy to better accommodate the complexities of power and new technology. **The goal is to dispel some false assumptions of power usage/efficiency, and in particular Power Factor, to help utility providers implement billing policies that have the intended effects and that support emerging energy efficiency technologies.**

Traditional Power Factor Measurement

When delivering power to buildings, alternating current (AC) circuits are used; *alternating* here describes how the charges behave in the wire, constantly and periodically reversing direction as opposed to direct current where the charges flow in only one direction. The most common way to depict AC power is using a waveform of a sine wave for the current and the voltage. Because power is defined as simply current times voltage, the result is a combination of the two waveforms. In an AC circuit, the waveforms for current and voltage may not necessarily be in sync with each other; they could be out of phase by some angle. The reason why a wave can be out of sync by an angle is that a sine waveform can be thought of as a deconstructed circle, with angles corresponding to points on the wave, as shown in figure 1 below.

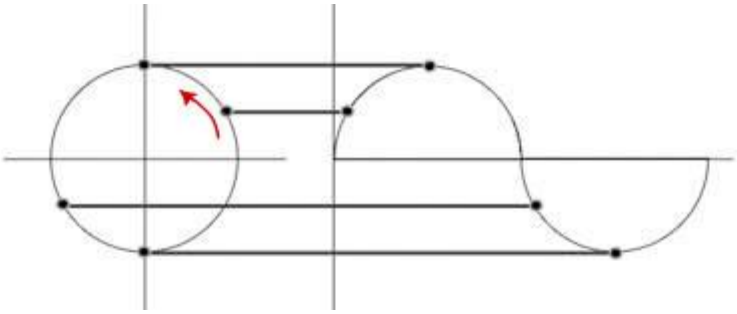

Figure 1: A circle with points at angles 30°, 90°, 210°, and 270° corresponding to a wave (http://www.visionlearning.com/library/modules/mid131/Image/VLObject-3544-060105030144.jpg).

Figure 2 below graphically displays generic waveforms of current and voltage with the red current waveform out of phase with the blue voltage waveform.

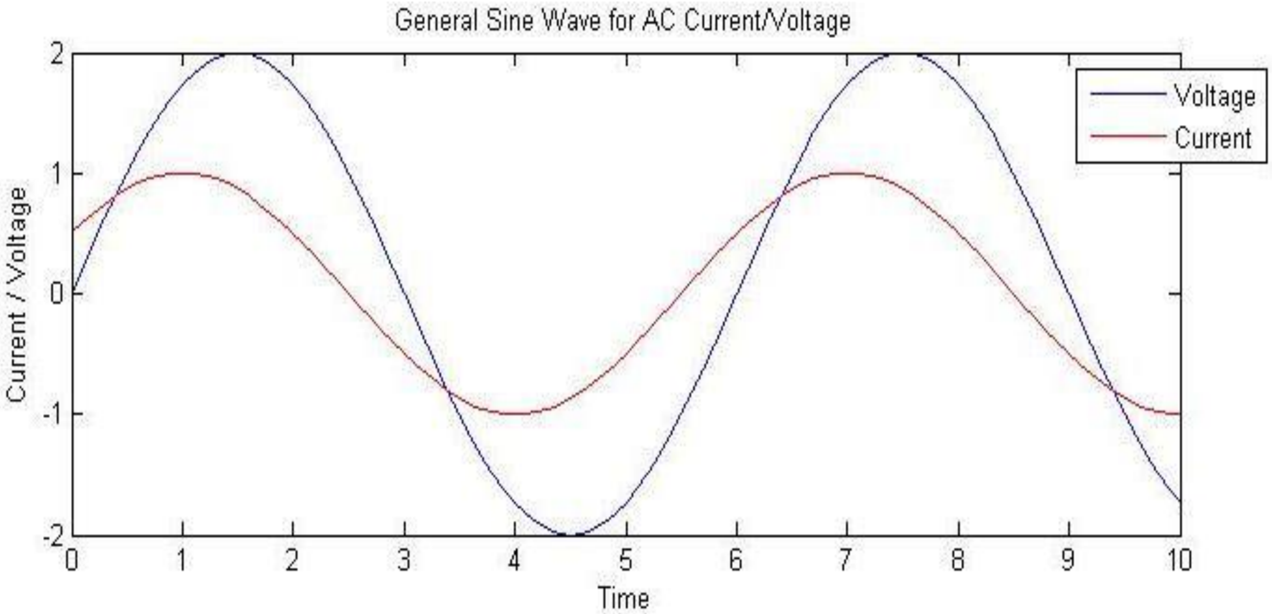

Figure 2: The waveform for current and voltage. Note how the current is out of phase with the voltage.

The Power Factor for AC power is derived from the simple formula that describes how to calculate power for AC circuits:

$$P = I * V * \cos(\varphi) \tag{1}$$

The Power Factor is the *cos(φ)* term in the equation where φ is the phase angle between current and voltage. There is good reason to calculate this power factor because AC power is always fluctuating, and it is important to understand that the current and voltage are not exactly in sync. The cosine of a 90° angle is 0 while the cosine of a 0° angle is 1. Therefore, the Power Factor will be between 0 (at 90°, indicating that the two waveforms are completely out of sync) and 1 (at 0°, indicating that the two waveforms are completely in sync. Equations (2) and (3) below show how the phase angle can make difference in power calculation.

$$P = I * V * \cos(90°) = I * V * 0 = 0 \tag{2}$$
$$P = I * V * \cos(0°) = I * V * 1 = I * V \tag{3}$$

Equation (2) is the situation where the current and voltage are completely out of sync, and thus there is zero output power. Equation (3) is the situation where current and voltage are completely in sync, giving maximum power output. Calculating the cosine of the phase angle difference between them describes the efficiency of power output. In other words, as the Power Factor reaches the ideal of 1, or unity, the power is most efficient whereas a very poor Power Factor approaching 0 is drawing excessive current to maintain the same amount of power, assuming voltage is constant.

Power Factor Is Not Sufficient

While determining the Power Factor is certainly helpful in describing efficiency, it is not sufficient for power measurement because it is unit-less. Power has several key elements to consider, such as reactive power and inductance. Reactive power is power that does no work, but it exists and needs current.

> The portion of power that flows into the load then back out is called **reactive power**. Since it first flows one way then the other, *its average value is zero*; thus, reactive power contributes nothing to the average power to the load. [new paragraph] Although reactive power does no useful work, it cannot be ignored. Extra current is required to create reactive power, and this current must be supplied by the source; this also means that conductors, circuit breakers, switches, transformers, and other equipment must be made physically larger to handle the extra current. This increases the cost of a system. (Robbins & Miller, 2004 , p.573)

In order to better understand Power Factor, it is helpful to show it as a triangle with real power (watts), reactive power – volt-amps-reactive (VAR) and apparent power – volt-amps (VA) as the three sides, as shown below in figure 3.

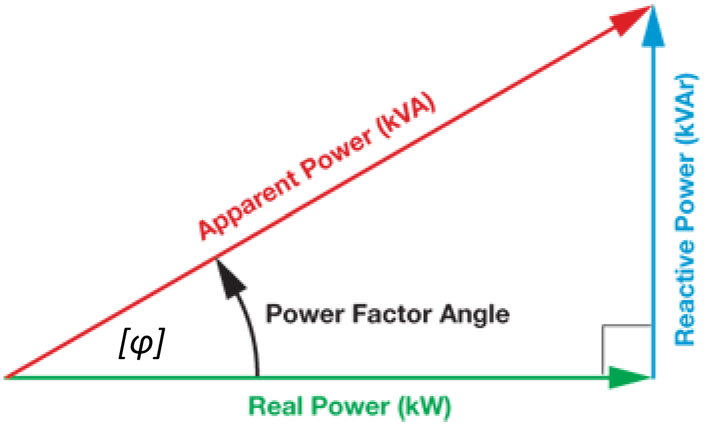

Figure 3: The Power Factor triangle showing the relation between real, apparent, and reactive power as well as the Power Factor angle. The φ in brackets was added to show the Power Factor angle (http://www.oru.com/images/content_images/reactivepowernew.gif).

From equation (1), the *cos(φ)* term is used to describe Power Factor where φ is the Power Factor angle (also the phase angle between current and voltage). The cosine of an angle when described in terms of right triangles is simply the adjacent side (relative to the angle) divided by the hypotenuse. From figure 3, this is

$$Power\ Factor = \cos(\varphi) = \frac{Real\ Power\ (kW)}{Apparent\ Power\ (kVA)} \tag{4}$$

The triangle model is a more complete explanation of how the Power Factor is derived, and the model also illustrates how apparent, reactive, and real powers are related.

Industrial Facilities Need More Complex Power Assessment

The simple power formula (1) seems to be practical in describing efficiency. Since residential electrical needs are generally not too far from unity, they may be billed in kilowatt-hours. On the other hand, industrial facilities are more often fined if their Power Factor is calculated to be too near 0, when the phase angle between voltage and current is close to 90°, to be efficient. This appears to be quite logical, but the reality is far more complex.

Leading vs. Lagging Power Factor

Power Factor can be described as either leading or lagging, which describes how the phase angle appears between current and voltage. A leading Power Factor means that the current is ahead of the voltage whereas lagging Power Factor means that the current is behind the voltage when graphed on a current-voltage versus time graph. Whether the Power Factor is leading or lagging depends on the type of load used in the circuit. In a circuit with a purely resistive load, the current and voltage are in phase with each other. Current leads voltage with a capacitive load. Current lags voltage with an inductive load.

Inductive Loads

One complication that industrial facilities face is that heavy machinery, motors, fans, lights, and heater coils are almost 100% resistive, creating more inductance, which draws more current. Inductance is said to cause a lagging current. Inductive lagging loads are almost always the case in the real world because of motors, especially in factories. In an inductive circuit, when AC is applied, there is always an opposition to current flow called inductive reactance (Fardo & Patrick, 2009, p. 37), which depends on the inductance and the rate of change of current. Inductance is the property of a conductor in which a change in current creates a voltage in itself and nearby conductors. This voltage will resist the change in current coming into the inductor, which means that the inductive load needs to draw more current, creating a lower Power Factor. Since inductance causes a Power Factor to move toward 0 and draw more current, power companies are correct in wanting to discourage that excessive current draw, which could cause a potential overload as seen in Figure 4 below.

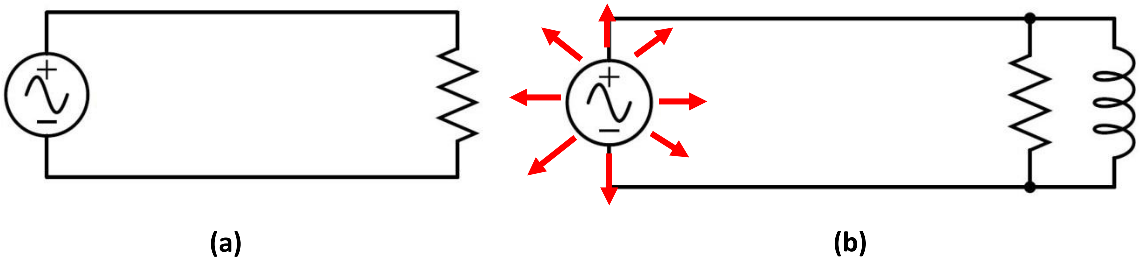

Figure 4: **(a)** With a purely resistive load in an AC circuit, the current rating is nominal. **(b)** When an inductive load is added to the AC circuit, the power rating will be the same, but it will draw too much current, thus exceeding the current rating, which can cause the power supply to be overloaded.

Capacitive Loads

What capacitors basically do is store some of the excess electrical energy, then alternately charge and discharge, in order to create better balance while the electricity is in use. They cause what is called a leading current. Unfortunately, a Power Factor (PF) does not take into consideration lagging vs. leading because the cosine of a negative angle is equal to the cosine of that positive angle (ex: cos(60) = cos(-60)). Yet the lagging current instead of leading current simplistically might be considered negative. **In other words, like wind, it has magnitude and direction, which is described mathematically as a vector. A negative direction should not be counted against a client**. However, when calculated, the PF of either the positive or negative angle is near 0, which is typically undesirable, yet in reality, the load may be drawing very little current, which should be encouraged instead of being unfairly penalized. What should count is the load on the circuit, which is not even being calculated in the Power Factor. When considering lead vs. lag, it is clear that measuring only the PF is actually insufficient and may even be misleading for determining power usage.

Harmonic Distortion

Another complication is the presence of harmonic distortion. Harmonic distortion occurs when one has a nonlinear load, such as when semiconductors are used in the electronics. Because the voltage and current in an AC circuit are sinusoidal, harmonic distortion will change the shape of the waveforms by either constructively or destructively interfering via the addition of a frequency that is an integer multiple of the original or fundamental frequency. For example, if the fundamental frequency is 60 Hz (which is the North American standard for AC power), the first harmonic would be 2 * 60 Hz or 120 Hz, the second harmonic would be 3 * 60 Hz or 180 Hz and so on. Figure 5 below demonstrates how a pure sine wave can be distorted with the addition of a harmonic frequency.

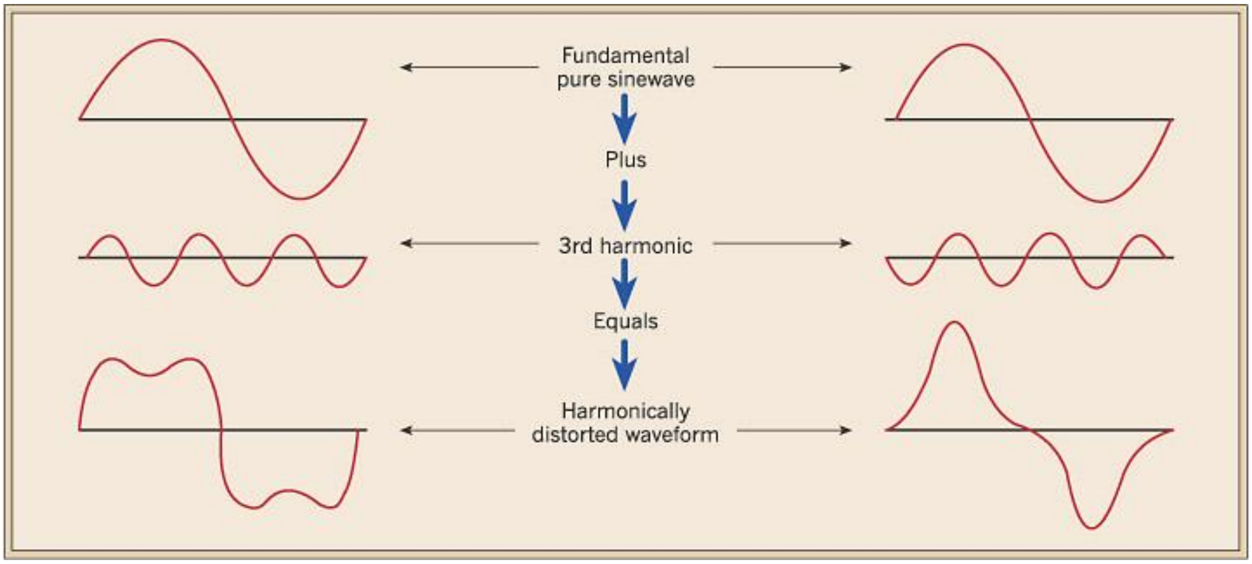

Figure 5: A pure sine wave plus its third harmonic will produce a resulting distorted waveform from constructive and destructive interference of the waveform. The third harmonics shown are shifted by 90°, resulting in two different distorted waveforms at the end due to differences in interference (http://ecmweb.com/site-files/ecmweb.com/files/archive/ecmweb.com/ar/606ecmINSIDEPQfig3.jpg).

There are actually two kinds of harmonic distortion that can occur: harmonic current and harmonic voltage. Harmonic currents refer to distortions occurring at the load, whereas harmonic voltages occur at the electric utility side. In AC circuits without nonlinear loads, the current is always proportional to the voltage and is thus linear, even if the current leads or lags the voltage based on whether the circuit is capacitive or inductive, respectively. With nonlinear loads, which all solid-state electronics have because of the inclusion of semiconductor devices, the current is not proportional to the voltage. Power supplies use diodes and silicon controlled rectifiers (SCRs) that can create leading or lagging loads, depending on the quadrant of the power sine wave. All of these complexities affect the Power Factor.

Peak Consumption Rate

One further complexity is the consumption rate. Power companies need to be able to know the peak consumption rate of all their consumers in watts so that the capacity and distribution ability can be calculated. **Electricity meters should measure peak demand as the highest 15-minute interval consumption rate computed as an average over a length of time.**

Instead, some manufacturers measure the highest wattage spikes. This is incorrect because there is a distinct difference between an averaging of 15 minutes and an instantaneous peak. Commercial consumers often have very high, but brief demand spikes as motors and heavy loads are switched on or off. While the magnitude is high, the impact to the utility/grid consumption rate is negligible because the spike durations are so short. Figure 6 below shows varying levels of power spikes.

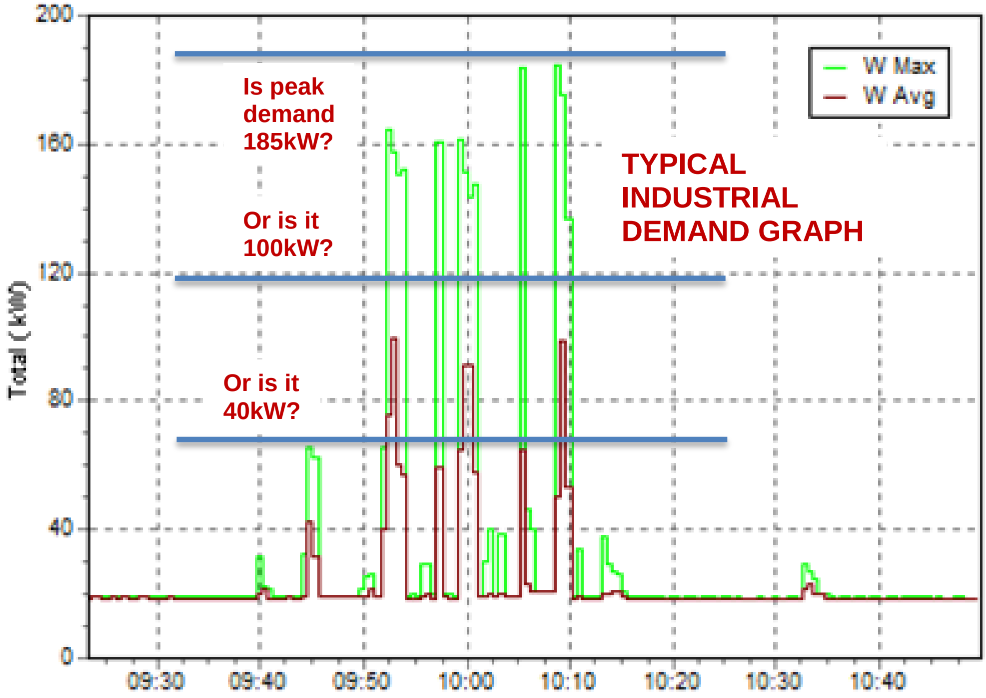

Figure 6: Example of a typical power consumption (or demand) graph from an industrial facility showing various power spikes at different times. It is not fair and accurate to simply measure the spikes instead of taking an average (Jacobs, 2013, slide 5).

Electric meters often compute root mean square (RMS) values for voltage, current, watts, etc., and these values are in turn included in the consumption calculations (used for peak determination). A further complication that is frequently misunderstood, even by meter designers, is that RMS measures can be greatly impacted by noise. A 10% noise figure on voltage 25% figure on current present a 3.5% over estimation of RMS power consumption. Since demand charges are frequently 3x to 10x larger than consumption, **correct measurement and calculation are critical**.

Billing/Fining Practices Should Be Reconsidered

While the idea of incentivizing companies by simply assigning penalties to correct their PF usage sounds logical, the answer is actually counter-intuitive because of the complex nature of power. In order to make power generation more efficient, power-consulting companies are creating an emerging technology that uses reactors to decrease the current. These reactors work as capacitors to reduce the load: "…a capacitor essentially opposes changes in voltage, or potential difference, across its plates. A capacitor in a circuit retards current flow by causing the alternating voltage to lag behind the alternating current, a relationship in contrast to that caused by an inductor" ("Reactance," 2013). **Inappropriately fining a company that is making an effort to conserve power use simply makes no sense.**

More Accurate Assessment Needed

Here is a typical scenario:

> Consider the following, Power Factor is basically an angle based on the ratio of VAR to Watts. The power company averages the angle. They should average the angle with a magnitude (this is roughly based on 50% running, 50% idle. In actuality, the customer is probably running 9-10 hours/day and is off 14-15 hours/day. When turned off, they have a 'bad' Power Factor. What's worse is that the bad Power Factor is actually leading .

That "bad Power Factor" that is leading is in reality beneficial to power consumption because it is occurring when the power is turned off. To fine a company for turning off the power seems ludicrous, yet that is what is happening in many cases. A recent case study shows a clear example:

> Assume a factory operates for 12 hours everyday at 500KW and -200KVAR (lagging).
> The PF is 0.93 with an apparent power of 539KVA.
> Consider two different 12 hour nighttime cases:
> 1. They drop to **50KW/+100KVAR** (leading) with PF of 0.48 and apparent power of 11.2 KVA
> 2. They drop to **50KW/-100KVAR** (lagging) with PF of 0.48 and apparent power of 11.2 KVA
>
> In both cases the power company would penalize for an average PF of 0.68.
> ***These cases are very, very different but the penalty would be the same!*** (Jacobs, 2013, slide 9)

What is clearly needed is a Power Factor averaged as a vector quantity, using hourly or similar readings to assess Real Power and Reactive Power and then determine the average Power Factor as Real Power Average/Apparent Power Average. (See Figure 7 on next page.)

Doing vector or averages gives a different result:
Case 1 (*12 hours night, 12 day*): (50+500, 100+(-200)) = (550,-100) ➔ **PF = 0.94**
Case 2 (*12 hours night, 12 day*): (50+500, -100+(-200)) = (550,-300) ➔ **PF = 0.878**

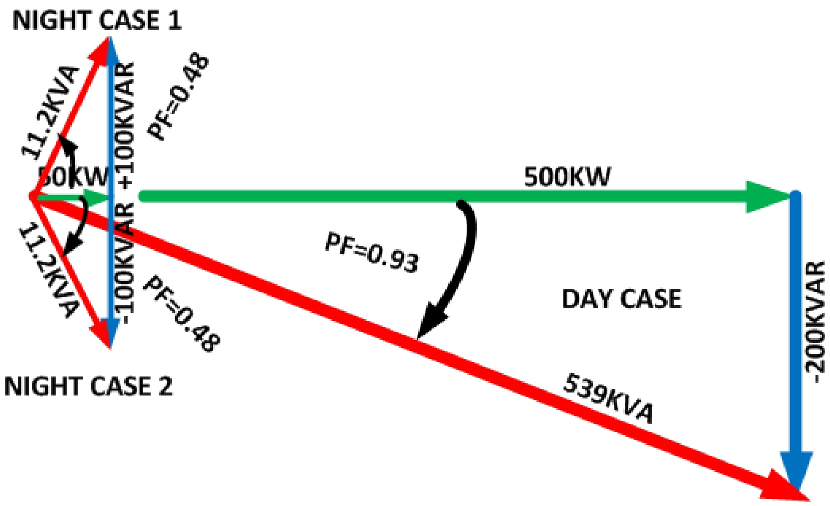

Figure 7: During the day, the power factor would be 0.93, which is acceptable according to most power companies; however, at night when most of the loads are off, the power factor drops to 0.48 for both leading and lagging cases, normally undesirable outcome. However, because the majority of the loads are turned off, the system is not drawing as much current, thus using less overall power (Jacobs, 2013, slide 9).

Another example below from Orange and Rockland Utilities, Inc., illustrates how a reactive power charge of 95% could harm a customer while calculating for billable kVa offers relief.

Maximum **Real Power** for billing period = **1,000** kW

Reactive Power at the time of maximum kW demand = **750** kVAr

Apparent Power = SQRT [(1,000 kW)$_2$ + (750 kVar)$_2$] = **1,250** kVA

Power Factor = $\frac{1,000 \text{ kW}}{1,250 \text{ kVA}}$ = 0.80 = **80%**

Because the power factor is below 95%, a charge of $0.40 per kVar is applied to the bill. To lessen the charge, Orange & Rockland subtracts 1/3 of the kW (real power) when calculating for billable kVar (reactive power), as shown below.

Billable kVar = 750kVar – 1/3(1,000) = **416.7** kVar

Reactive Power charge = 416.7kVar X $0.40 = **$166.68**

(“Calculating Power Factor,” 2007)

What this means is that a low PF, or ostensibly “bad” PF, at a small Apparent Power should not be counted as much as a slightly bad Power Factor at a high Apparent Power. The assessment needs to be adjusted for better accuracy. Penalizing an industrial facility for a very bad PF when the plant is basically shut down and power consumption is much lower (perhaps well over 100 times) than the business hour consumption is not only unfair, but ironically, it accomplishes exactly the opposite of the intention. The customer is being fined for conservation, or cutting down usage, instead of being fined for overconsumption.

Conclusion

There is clearly a need for more accurate assessment of power usage, and the practice of automatic fining for Power Factors near 0 needs to be reevaluated. The Power Factor may be adequate in most cases, but for industrial facilities using new reactive, power-saving technology, it is absolutely vital to revamp the assessment. For instance, according to executives at Simplure, a company specializing in power conservation, technology is currently being developed to make the power conditioning systems able to respond to load level (basically disenage/engage based on load/time of day). There are simple systems in use today called AutoVARs that dynamically add/remove capacitors for this very reason. The irony is clear:

> Simplure provides power conditioning solutions that are targeted at:
>
> - Harmonics mitigation
> - Phase balancing
> - Demand peak reduction
>
> There are new solutions far more complex than simple Auto-VAR systems that generally involve cross-phase coupled transformers. They perform very well under high load (where it matters) but during idle low demand periods they can produce small leading currents (capacitance), which result in lower PF (Jacobs, 2013, slide 13)

Power usage is clearly very complex. Sometimes the very solution that is actually conserving energy can be assessed as being just the opposite. While technology is improving, it is also vital to reexamine the simplistic and sometimes unfair methods of measurement, fining, and billing practices. Some suggestions to consider are the following:

1) **Address leading vs. lagging loads when computing PF**
2) **Do a weighted/vector average of PF to take into account demand level throughout the day**
3) **Consider a billing formula based on Apparent power (KVAhrs)**

Doing assessments based on averages rather than spikes and calculating the Power Factor more accurately with a weighted formula so that PF fines are more fair will go far to help reward power conservation.

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Graphics

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