Technical Note 174

Introduction to power factor

What is it and why should we care?

Mechanical rooms, and HVACR equipment in general, are responsible for heating and cooling mechanical tasks allowing for comfortable buildings. While the mechanical side is typically well understood and appreciated by those in charge of facilities like hospitals or large commercial buildings, the electrical impact of the equipment at times may be overlooked. Yes, there is the utility bill angle, every month a large portion (often over 40%) of the electric bill is a direct result of operating mechanical equipment. But there is much more to the electricity usage and bill than just a total kWh and a dollar amount. Hidden in the electrical details is power factor. Ideally, a system is designed up front to optimize power factor, as this will have a long-term positive impact. However, there are actions that can be done to existing installations to improve power factor.

Why do we care about power factor? In an electrical system, bad power factor can have many adverse effects. Power factor is directly related to facility efficiency, electrical load capacity, regulatory compliance, environmental impact, and utility charges or incentives. This paper looks at explaining what power factor is, why good power factor is important, costs of bad power factor, and types of solutions to improve power factor. We will also review the difference between displacement power factor and true power factor.

Power factor (PF) is a measure of how efficiently electrical power is being consumed or utilized in an electrical system. The three power components of Alternating Current (AC) are real power, reactive power, and apparent power. Real power is measured in watts (W) and is the working component. Reactive power is measured in volt-amperes-reactive (VAr) and is not part of working power. Apparent power is the combination of real and reactive power and is measured in volts and amperes (VA). When looking at a system with only one frequency (no harmonics), the Power Factor (PF) is equal to Real Power / Apparent Power. This applies to an ideal system with only the fundamental frequency of 50 or 60 Hz. Power factor using only the fundamental frequency is known as displacement power factor. Power factors that combine fundamental and harmonic frequencies are known as true power factor. Sometimes true power factor may also be known as total power factor or net power factor. True power factor will be addressed later in this document. For a simple system, the Displacement Power Factor equation are:

$$PF = \frac{Real\ Power\ (P)}{Apparent\ Power\ (S)} = \frac{W}{VA}$$

Power Factor base equation

$$VA = \sqrt{W^2 + VAR^2}$$

Apparent Power equation

$$PF = \cos\theta$$

Power Factor trig relationship

When we look at the components in phasor form using power vectors, we get the power triangle shown in Figure 1.

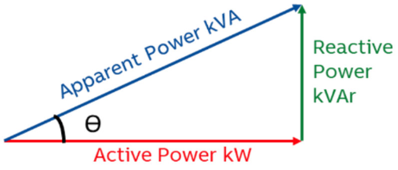

Figure 1 Power triangle

kW - Active Power is the power that performs useful work.
kVA - Apparent Power. Vectorial summation of kVAR and kW.
kVAR - Reactive Power. It is the power needed to produce the magnetizing flux.

If a system has only resistive loads, the power factor would be unity or 1. When the system has inductive loads like motors, transformers, and fluorescent lighting, the power factor moves to a lagging power factor. For a lagging power factor, the phase current always lags the phase voltage, and the power angle theta (θ) is positive. For capacitive loads, the PF is leading. Most systems have a lagging power factor, but when corrective solutions for lagging PF, such as capacitors, are miss-applied a leading power factor can occur. The crucial difference between a leading and a lagging power factor is that in the case of a leading power factor, the current leads the voltage and power factor is positive. In the case of a lagging power factor, the current lags the supplied voltage and power factor is negative. Power factor (PF) is defined as the cosine of the phase angle between voltage and current in an AC circuit. A power factor of 1 (unity) indicates perfect efficiency, where all the power is being used to do useful work. Figure 2 shows a power factor of 1 or 100%. The voltage and current are in phase, and the power is positive active power. Figure 3 shows a lagging power factor of 0.8, or 80%. The current is lagging behind the voltage, and 80% of the power is active, with 20% reactive power. Figure 4 is the power triangle for a lagging power factor of 0.8, or 80%.

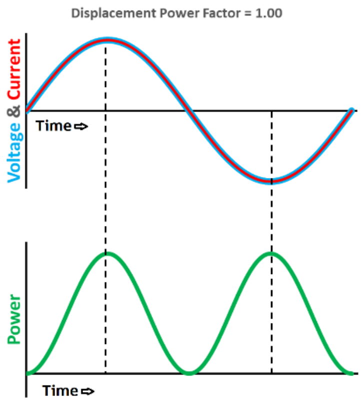

Figure 2 Power factor 1

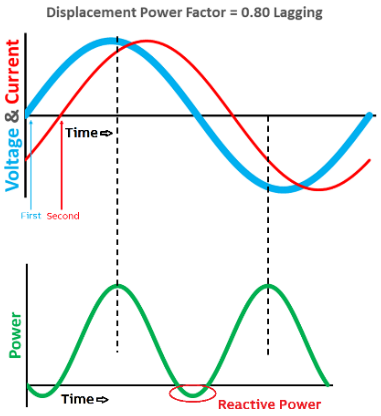

Figure 3 Lagging Power Factor 0.8

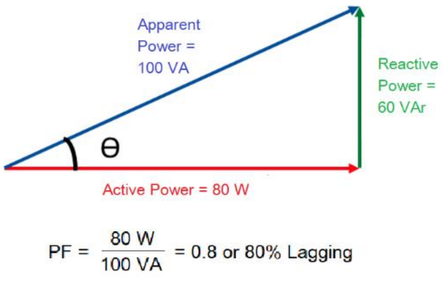

Figure 4 Power Triangle

Why is good power factor important?

A simple answer to the above question is: For a building's mechanical room with various mechanical equipment such as pumps, fans, compressors, and HVACR systems; a good power factor is important for efficient operation and energy management. A good power factor means the utility bill may be lower, the building will run more efficiently at several levels (from transformers down to motors), and the facility may have additional capacity leftover for future expansion. In addition to the positives within a building, there are positives from the utility's perspective.

A high-power factor indicates efficient utilization of electrical power, reducing energy losses, and improving system efficiency. Utilities often penalize low power factor because it requires them to supply more current to meet the same power demand, leading to higher distribution costs. Many government agencies across the world, such as the U.S. Department of Energy, look at power creation and efficient power utilization as a real solution for long-term sustainability. Currently, power factor penalties are usually applied to larger power consumers and are dependent on the utility. Due to the variance of each utility, check with the local utility to determine what applies and if any savings could occur by increasing power factor.

The power factor penalty, including the threshold value and the calculation method, varies depending on the utility's policies and regulatory requirements. A low power factor indicates that a customer's electrical system is less efficient in using the electricity supplied to them. These penalties are intended to reflect the additional costs incurred by the utility due to inefficient power usage. In many cases, a utility is charging their customer based on real power (kW) consumption even though the utility must provide the apparent (VA) power. Charging a power factor penalty allows the utility to collect additional funds to cover the negative impact of low power factor. A low power factor reduces utility generation and transmission capacity.

Utilities may use an average of the highest demand power factor readings per billing month to determine peak billing demand. Some utility companies will give discounts for good demand power factor and charge for bad demand power factor levels. In extreme cases, the utility may not be obligated to deliver electricity to customers at any time when the demand power factor is below the minimum level. Usually demand charging is done on large power users only due to the cost of monitoring equipment, which is used to collect data on a facility's power factor. As the power structure is upgraded over time and the cost of monitoring equipment is reduced, it is expected that demand charging will become more prevalent in the future for smaller power users.

By increasing the power factor, a facility's system capacity is increased because of lower system losses. With lower losses, the facility may be able to add additional loads without increasing its power system. A high-power factor allows the electrical system to minimize voltage drops and run direct across-the-line motors cooler, more efficient, and with an increase in capacity and starting torque.

Table 1 provides an example with calculations for a 75 kW, 480V system load and the effect of the displacement power factor, not including harmonics. On a 75 kW system, reducing the apparent power to improve the power factor from 60% to 90% reduces the power transformer from 175 kVA to 100 kVA, the load amps from 151 amps to 100 amps, and the wire sizing from 2/0 to 3 AWG. Other savings include electrical billing, power factor penalty fees, power distribution equipment costs, and component life expectancy.

Table 1 Effects of power factor

kW	75	75	75	75	75	75	75	75
Power Factor	100%	90%	85%	80%	75%	70%	65%	60%
kVAr	0	36.3	46.5	56.3	66.1	76.5	87.7	100
kVA	75.0	83.3	88.2	93.8	100.0	107.1	115.4	125.0
Load Amps	90	100	106	113	120	129	139	151
Transformer	100 kVA	100 kVA	125 kVA	125 kVA	125 kVA	150 kVA	150 kVA	175 kVA
NEC Wire Size @ 75 °C	3 GA	3 GA	2 GA	2 GA	1 GA	1 GA	1/0	2/0

Table 2 provides an example of cost multipliers for different displacement power factor. This example is considered to be conservative, as many utilities charge penalties sooner. At a displacement power factor of 85% (0.85), the cost multiplier is 1. When the displacement power factor is above 0.85, the utility gives cost credits through price reduction, and when it is below 0.85, the utility fines the user by increasing the cost per kWh of usage. If we assumed the 75 kW system averaged 60 kW per month, the factor of 60% (0.60) would be 1.1785. If the power factor is improved to 90% (0.9), the new multiplier is 0.981, reducing the electrical cost by over 19%. This is a basic look at potential savings; other factors can affect the cost. Contact the local utility for more information.

Table 2 Power factor cost multipliers

Rate schedule for 50 kW per month minimum usage - Indianapolis Power & Light Company													
Power Factor	Multiplier		Power Factor	Multiplier		Power Factor	Multiplier		Power Factor	Multiplier		Power Factor	Multiplier
1	0.951		0.9	0.981		0.8	1.023		0.7	1.0835		0.6	1.1785
0.99	0.9535		0.89	0.9844		0.79	1.0277		0.69	1.0913		0.59	1.1897
0.98	0.9562		0.88	0.9881		0.78	1.033		0.68	1.0992		0.58	1.2025
0.97	0.959		0.87	0.9919		0.77	1.0386		0.67	1.1075		0.57	1.2159
0.96	0.9618		0.86	0.9958		0.76	1.0442		0.66	1.1161		0.56	1.23
0.95	0.965		0.85	1		0.75	1.05		0.65	1.1225		0.55	1.2455
0.94	0.9677		0.84	1.0041		0.74	1.0563		0.64	1.1347		0.54	1.2607
0.93	0.981		0.83	1.0085		0.73	1.0694		0.63	1.1447		0.53	1.2773
0.92	0.9741		0.82	1.0131		0.72	1.0764		0.62	1.1551		0.52	1.295
0.91	0.9774		0.81	1.0178		0.71	1.0835		0.61	1.1661		0.51	1.3136

The power factor directly affects the efficiency, capacity, and overall performance of standby generators, such as those used for hospitals or other building types that require continuous power. Generator kVA rating is based on unity power factor, but when a lagging power factor is present, higher losses in the generator windings cause lower efficiencies. Generators need to be increased in size to support the load increasing cost and because the generator must supply both real and reactive power. Leading power factor can make a generator unstable and trip offline, which can have very detrimental consequences for building types like hospitals.

True Power Factor

Harmonics are sinusoidal voltages or currents that have frequencies that are integer multiples of the fundamental frequency of the power system. Up until this point, this technical note has assumed an ideal electrical system, with the current and voltage waveforms as perfect sinusoids at the fundamental frequency (typically 50 Hz or 60 Hz) only. However, in real-world systems, non-linear loads (such as variable frequency drives, LED lighting, medical equipment, and computers) introduce harmonics into the system. Harmonics can distort the voltage and current waveforms, causing issues such as increased losses, overheating of equipment, interference with communication systems, and decreased power quality. The addition of the kVAd vector representing the harmonic distortion, as shown in Figure 5, creates a new power triangle for a true power factor with harmonics.

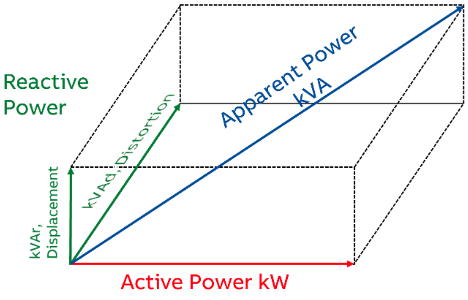

Figure 5 Power triangle for a true power factor including harmonics

kW - Active Power is the power that performs useful work.
kVA - Apparent Power. Vectorial summation of kVAR and kW.
kVAR - Reactive Power. It is the power needed to produce the magnetizing flux.
kVAd – Reactive Power Distortion. Harmonic component of reactive power.

The relationship between true power factor and harmonics is complex. Harmonics can affect the true power factor of a system by causing distortion in the voltage and current waveforms. Non-linear loads, which are often the source of harmonics, can create distorted current waveforms that lead to a poor power factor. Power factor correction capacitors, commonly used to improve power factor, may not be as effective in the presence of harmonics because they are typically designed to correct for displacement power factor (caused by phase shifts between voltage and current at the fundamental frequency) but not distortion power factor (caused by harmonic distortion at other frequencies). For a more detailed explanation of the effects, refer to IEEE 1459-2010.

The new base formula for True Power Factor requires the addition of the harmonic component, including the total harmonic current distortion is:

$$Power\ Factor = \frac{\cos\theta}{\sqrt{1 + {THD_I}^2}}$$

- $\theta = Displacment\ angle\ between\ fundamental\ Voltage\ and\ Current$
- $THD_I = Total\ harmonic\ curremt\ distortion$

Power factor and harmonics are two important concepts in electrical engineering, often discussed in the context of power quality and efficiency in electrical systems. True power factor accounts for the harmonics thus reducing the total harmonic content contributing to the efficiency of the electrical system. Some utilities can monitor the true power factor but usually displacement power factor is used for billing purposes.

Solutions

Conducting energy audits helps identify areas of inefficiency in power usage. This involves assessing energy consumption patterns, identifying wasteful practices, and determining opportunities for improvement.

Resolving a lagging power factor involves improving the efficiency of an electrical system by reducing the phase difference between voltage and current and the total current harmonics in an AC circuit. This is commonly done in systems where inductive loads, such as motors and transformers, cause the current to lag behind the voltage.

Motors can have a power factor of 0.85 at full load but can drop as low as 0.20 at 30% load. By minimizing the operation of idling or lightly loaded motors power factor can be improved. Replacing standard motors with energy-efficient motors can improve the power factor if applied correctly. A motor must be operated near its rated load in order to realize the benefits of a high power factor design. A very low power factor is caused by running induction motors lightly loaded. Sizing motors for the load or using a variable frequency drive (VFD) can improve overall performance.

Use of six (pulse) drives with internal 5% equivalent impedance, such as the ABB ACH580 improves power factor and saves energy. The average displacement power factor can be as good as 0.98 and true power factor at full load is around 0.91 due to the harmonics produced by the VFD. When using a VFD the AC supply line only must supply real power because the voltage and current remain almost perfectly in phase with very little displacement, and the displacement power factor can be near unity. Unfortunately, diode-based six-pulse rectifier VFDs introduce harmonic current distortion that can have THD_I in the range of 35–45 percent. The harmonic currents negate some of the power factor benefits of the VFD.

Active front end (AFE) drives like the ABB ACH580 ULH use IGBTs, rather than diodes, to rectify the incoming power. The active front-end drives have a lower (better) THD_I than standard diode-based rectifier designs, as low as 3 percent. AFE drives can have a unity power factor throughout most of their power range. The ACH580 ULH drives can adjust the input power factor, positive or negative, through programming. This allows the drive to use its remaining capacity to further correct the building's power factor whenever the drive is not running at full load. The drive can be programmed to create kVAR to counter reactive power created by other components, thus improving the facility's displacement power factor.

Capacitors can be used to offset the inductive reactive power in the system. Capacitors generate leading reactive power, which balances out the lagging reactive power of the inductive loads. Fixed capacitors or capacitor banks at specific locations in the system provide a continuous correction. The size is based on the reactive power requirements of the loads, which are permanently connected to the system. Capacitors may not be effective unless designed for distortion power factor caused by harmonic distortion. Automatic power factor correction systems continuously monitor the power factor of the system and automatically switch capacitor banks on or off to maintain a target power factor.

Active harmonic filters can be used to provide active power factor correction. They use power electronic converters to actively control the flow of reactive power in the system.

Summary

Power factor is a crucial parameter in electrical systems, indicating the efficiency of power utilization and impacting both energy costs and equipment performance.   When looking at the power industry, the ability to save energy through more efficient use of power is as important as the ability to create more energy and reduce operational expenses. Improving the efficiency of power usage is crucial for conserving energy and reducing overall electricity consumption. In the future, as power systems are upgraded with better metering abilities, more power companies will use increased costs to encourage users to become more efficient, thus saving energy. More efficient use of energy reduces CO2 emissions, supporting decarbonization strategies.