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Power Factor Correction's Effects on Electric Networks' Performance

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I. Introduction

Power factor correction could be defined as a technique for managing reactive power to improve the performance of the AC power system. Improving the power factor allows for economic and technical advantages. A low power factor implies a high consumption of reactive power and increases the losses of the lines and transformation elements. From an economic point of view, this may mean the need to use cables with a larger section and even the need to replace the transformation equipment if the total power demand exceeds the capacity of the existing equipment. The penalties that the supplying firms impose on their customers as a result of low power factors should be taken into account as an additional economic consideration. National power supply companies implement a tariff structure that requires the consumed reactive energy to be paid in specified amounts based on the power factor as well as the supply voltage level. Additionally, an installation's power factor can be enhanced to make better use of electrical transmission and distribution lines. Power factor adjustment is typically employed for financial reasons. [1]

II. Power Factor

Power factor (PF) refers to the ratio of true power to apparent power in a circuit or distribution system. True, reactive, harmonic, and apparent (total) power make up any AC circuit. True power is the power measured in kilowatts (KW) and used by motors, lights, and other equipment to generate practical work. Reactive power is the power that inductors and capacitors store and release, expressed in KVAR. Power lost to harmonic distortion, expressed in VA or kVA, is known as harmonic power. The total (apparent) power delivered to the inductive equipment is the vector sum of the previously mentioned three powers and is measured in KVA.

The displacement power factor (DPF) is a measure of how effectively electrical power is being converted into useful work, specifically in relation to the phase difference between voltage and current in an AC electrical system. The value of the power factor theoretically ranges from 0 to 1 (or 0% to 100% when expressed as a percentage). A power factor of 1 (or 100%) indicates that all the power supplied is being converted into useful work (active power). A power factor of 0 means that all the supplied power is reactive power. This situation indicates that the system is not performing any useful work, as reactive power is used to maintain electric and magnetic fields in inductive and capacitive components.

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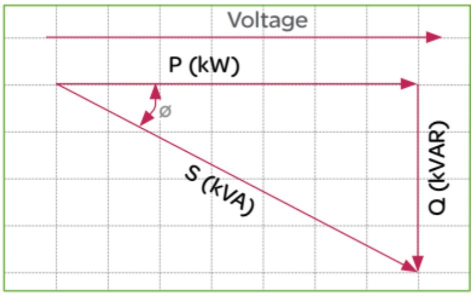

Figure 1. Power components' relationships

The distortion power factor is the ratio between the true power and the apparent power due to the total harmonic distortion THD. The power components' relationships are shown in Figure 1. It shows that the reactive component is 90 degrees out of phase with the applied voltage, whilst the active power component is in phase with it.

The power factor has two main components: displacement PF and distortion PF. It is typically calculated by taking both components into account, with a formula involving them both as follows.

$$PF_{displacement} = \frac{True\ power\ P}{Apparent\ power\ S}$$

$$PF_{distortion} = \frac{1}{\sqrt{1+THD^2}}$$

$$PF_{total} = PF_{displacement} \times PF_{distortion}$$

Where:

$PF_{displacement}$ Is the displacement power factor which is the ratio between the true power and the

apparent power due to the phase displacement between current and voltage.
$PF_{distortion}$ Is the distortion power factor which is the ratio between the true power and the apparent power due to the total harmonics distortion
PF_{total} Is the total power factor that considers both displacement and distortion.
THD Is the total harmonics distortion that quantifies the extent of harmonics present
This shows that a high THD can reduce the true power factor significantly, even if the displacement power factor is close to 1.

III. Power factor correction

Power factor correction (PFC), in essence, is a voltage regulation system that enhances stability by making the best corrections to the (sinusoidal) voltage signal. It also primarily functions to remove distortions of the electrical network on the absorbed current to prevent the emergence of harmonic currents that could be harmful to the network. It will also play the part of bringing the voltage and current into phase. To put it another way, A PFC transforms the power supply from a non-linear load to a pure resistance, allowing the network to recognize it as such [2]

3-1 Displacement power factor correction

The power factor can be enhanced by raising the active power component or decreasing the reactive component. Of course, boosting the active power component only for power factor correction is not economically possible. Reducing reactive power is the only practical technique to increase the system's power factor. One option to lessen this component is to provide reactive power close to the load as shown in Figure 2 (b). This process improves the power factor from the point where the reactive power source is connected, which means that less reactive power needs to travel through transmission lines, reducing current and hence lowering losses. While delivering it on the power supply side, Figure 2 (a), reactive power will flow over extended distances, resulting in increased power losses owing to line resistance.

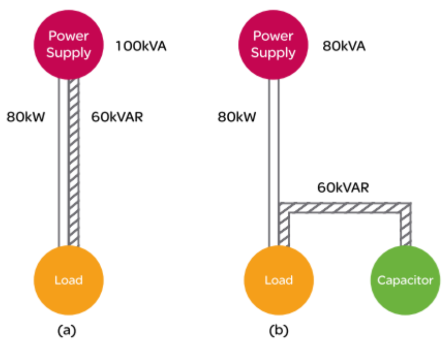

Figure 2. Reactive power (on the power supply side vs. on the load side) [3]

One must first grasp how energy is stored in capacitors and inductive devices in order to comprehend the power factor. In AC circuits, the voltage varies in a sinusoidal fashion. As time passes, the value of this voltage varies. The appliance plugged into the power source determines whether the current alternates as well. The capacitor accumulates energy in its electrostatic field at this period, whereas the inductive device releases energy from its electromagnetic field. The inductive device absorbs energy while the capacitor releases energy as the voltage drops after reaching a maximum. Consequently, there will be a magnetizing current interchange that occurs between an inductive device and a capacitor when they are placed in the same circuit; that is, the leading current that the capacitor takes neutralizes the magnetizing current that the inductive device receives. Since the capacitor provides the magnetizing needs for the inductive device, it can be regarded as a Kilovolt-Ampere-Reactive (KVAR) generator. We can better comprehend the usage of capacitors for power factor adjustment if we think of them as kilovolt ampere-reactive (KVAR) generators.

Synchronous motors and shunt capacitors are the two widely used techniques for power factor correction. Both have uses; the synchronous motor is mostly used in new and big motor units, while the capacitor approach is typically more cost-effective and useful for facilities that are already in operation [4]. It fulfills two functions by providing mechanical power in addition to reactive power correction.

In industrial electrical installations, capacitors—which are grouped together to create capacitor banks—are a fundamental component of power factor correction.

The installation of capacitors for power factor correction is not a one-size-fits-all solution; it requires careful consideration of various factors specific to each electrical installation. It is clear that only the compensation system—an automatic centralized power factor correction supply—should be used in installations with numerous loads, where not all loads are operating simultaneously, and where there isn't a continuous absorption of reactive power because of work cycles. In industrial systems, this is most frequently the case.

Sizing capacitor banks for power factor correction is a critical process that requires careful calculation and consideration of the specific load cycles of a plant. The implementation of capacitor banks in steps is indeed a critical aspect of achieving effective power factor correction in electrical systems. This method enhances control precision and allows for better management of reactive power. The use of microprocessor-based regulators to control capacitor banks is a sophisticated approach to managing power factor correction in electrical systems. This technology allows for precise control of reactive power, optimizing the operation of capacitor banks and enhancing overall system performance. Resonance in electrical systems, particularly in industrial settings with inductive and capacitive components, can lead to significant issues. When the capacitive reactance XC and the inductive reactance XL are equivalent, resonance takes place.

In a series resonant circuit, the inductor (L) and capacitor (C) are connected in a single loop, while in a parallel resonant circuit, the inductor (L) and capacitor (C) are connected in parallel with each other across a common voltage source. Both series resonance and parallel resonance can coexist in the same electrical network. The size of capacitor banks in electrical systems can significantly affect system performance, particularly regarding resonance and harmonic distortion. Consequently, reducing harmonic currents and avoiding resonance are critical for enhancing the overall power factor of an electrical system [5].

3-2 Distortion Power Factor correction

The current and voltage waveforms taken from the network exhibit distortions known as "harmonics" due to the impact of non-linear loads such as transformers, DC voltage sources, and interrupted power supplies. Thus, sinusoidal waveforms with frequencies that are multiples of the fundamental frequency are generated by these non-linear loads [6]. Harmonics can lead to many problems among which is reducing the power factor. They draw increased current that is not contributing to real power, leading to higher apparent power. This decreases the power factor because the system now has a higher apparent power for the same amount of real power.

There are several techniques to perform power factor correction (PFC) in circuits with harmonics, including employing specific transformers or tuned harmonic filters consisting of capacitors and inductors. In this method, high voltage fluctuations and capacitors charge current pulses are created in the power system causing a high value of harmonic current to be drawn from the network [7].

Filters are also used to avoid electromagnetic interference by filtering undesired harmonics that the load may introduce into the AC system. Filters typically target harmonic values that are considered more active. Power factor is significantly improved when harmonics are controlled, particularly in systems with non-linear loads.

3-3 Distinctions between displacement and distortion power factor correction

Table 1 shows a comparison between displacement and distortion power factor correction. Both methods are frequently used in systems with both inductive and non-linear loads to improve power efficiency and minimize pressure on the electrical infrastructure.

Table 1. Comparison between displacement and distortion power factor correction

Aspect	Displacement PFC	Distortion PFC
Focus	Phase angle difference correction	Harmonic distortion reduction
Primary Cause	Inductive loads causing current to lag	Non-linear loads create harmonics
Devices Used	Capacitors, synchronous condensers	Harmonic filters, active PFC circuits
Power Factor Improved	Fundamental power factor	Total (or true) power factor
Waveform Effect	Reduces phase angle, aligns voltage & current	Smoothens current waveform removes harmonics

IV. Power Factor Correction's Effects On Network Performance

Power factor correction (PFC) significantly enhances the performance, efficiency, and reliability of electrical networks. Here's how PFC affects network performance across different aspects

- In electrical systems, losses in transmission lines are directly related to the current flowing through the lines. When the current flowing through a transmission line is reduced, the losses in the line decrease proportionally. This reduction in current demand helps to improve voltage regulation within the distribution system, ensuring that consumers receive stable and adequate voltage levels for the proper operation of their equipment.
- There has been widespread observation and documentation of increased equipment efficiency. One to six percent increases in efficiency have been observed. Lower voltage systems (220V or 240V), and installations with extremely low power factors, (0.60 to 0.65, are usually linked to higher increases.
- Motors tend to be more efficient when the power factor approaches unity. Power factor correction helps in achieving this unity power factor,

reducing losses and improving the overall efficiency of the motor. Motors also tend to be more efficient when operating at higher voltages. Higher voltages can reduce slip in motors (the difference between synchronous speed and actual speed) and lead to more efficient operation [8].

- Improving the power factor can lead to lower demand charges on electricity bills. A better power factor allows also for higher load-carrying capacities on existing circuits. Besides, correcting the power factor reduces reactive power flow in the system, which in turn decreases losses in transmission and distribution equipment.
- Power factor correction reduces the reactive power drawn by inductive loads in the system. By bringing the power factor closer to unity (1), the system can regulate voltage more effectively. Stable voltage levels resulting from power factor correction ensure that electrical equipment operates within their specified voltage ranges. This stability enhances the performance and efficiency of the equipment, ultimately leading to longer lifespans and reduced downtime
- While reduced conductor losses may not be enough to warrant installing capacitors, capacitor installation is advantageous, particularly in systems with long power lines or feeders, like older industrial plants or remote field operations. While the primary purpose of capacitors in power systems is typically to improve power factor (by compensating for reactive power), the reduction in conductor losses can be an added benefit.
- In circuits with inductive loads, the loads demand not only active (real) power but also reactive power. This reactive power demand causes reactive current to flow through the conductors, which contributes to the total current but does not perform useful work. Installing capacitors near inductive loads (typically motors, transformers, or other devices with coils) addresses this by supplying reactive power locally, thereby reducing the reactive current that must travel over long distances.

V. Mitigate power factor issues

Many utilities implement power factor surcharges to encourage customers to maintain a higher power factor. This practice serves two main purposes: promoting more efficient electricity use and allowing utilities to cover the increased costs associated with providing service to customers who operate with a low power factor. Often, these penalties only assessed power factors when they fell below 0.90 or 0.95, some even as low as 0.80. Without the financial motivation from penalties or incentives, many customers would likely avoid this cost. Utilities use different methods to incentivize higher power factors, often by integrating penalties into the billing structure or by adjusting how demand charges are calculated. When a utility bases demand charges on apparent power (kVA) rather than real power (kW), customers end up paying more if their power factor is less than unity (1.0). In areas where utilities use kVA-based demand billing, many consumers may not realize they're effectively paying a "power penalty" due to a low power factor. This lack of transparency can make it challenging for customers to understand why their demand charges are higher and what they can do to reduce costs. The rise of power factor penalties and kVA-based demand charges in utility rate structures reflects a broader shift toward energy efficiency and environmental responsibility, driven by both regulatory and market pressures. The Clean Air Act and competitive market dynamics are influencing these changes. By incorporating low power factor-related charges into their rate structures, utilities can separate the costs of reactive power from those of real power—a practice known as disaggregation—and ultimately reduce the base power prices they charge customers. Thus, Power factor (PF) surcharges are a strategic tool that utilities use to incentivize consumers to improve their power factor. The benefits of these surcharges are multi-faceted, leading to lower costs for both consumers and utilities [9].

Besides, many utilities employ a billing structure that charges customers based on their maximum metered demand, either in kilowatts (kW) or in kilovolt-amperes (kVA), depending on which measurement is higher. This approach reflects the demand that customers place on the utility's infrastructure and helps utilities manage their resources effectively. When the power factor (PF) is low, it indicates that a significant amount of reactive power is being drawn by the load, which increases the total apparent power (measured in kilovolt-amperes or kVA) relative to the actual power (measured in kilowatts or kW) being consumed [10].

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