Power Factor Correction

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1. Introduction

For many years electric utilities and large industrial plants have reduced electrical current demands by the use of capacitors to increase the power factor on large electrical loads. With the growing emphasis on the need to conserve electrical energy, there is increasing interest in power factor correction for three-phase motors, even on small installations.

2. Electrical Fundamentals

The study of electrical engineering theory is extremely complex. Fortunately, the practical application of electricity involves exact scientific relationships that follow precise physical laws, so the application engineer needs be concerned only with basic formulas and relationships.

To understand power factor, a review of electrical fundamentals may be helpful.

- Volt is the electrical unit of measurement used to express the electrical potential or force which causes current flow.
- Ampere is the term used to express the rate of electrical flow or current.
- Watt is used to express the power consumed.
- Ohm is used to express the resistance to flow of current in a circuit.

In alternating current systems, both voltage and amperage rise and fall thru cycles such as illustrated schematically in Figures 1 and 2. The number of cycles per second is referred to as the frequency (hertz).

The values which we measure for voltage and amperage in a circuit are actually mean values occurring during the cycle.

If the voltage and amperage are in phase, as in Figure 3, the power consumed (watts) is equal to the product of the volts times amps. If, however, the voltage and amperage are out of phase, as in Figure 4, the product of volts times amps is only “apparent power” (volts-amperees), and the actual power (watts) is some lesser value, the reduction being determined by the degree to which current and voltage are out of phase.

Power factor is defined as the ratio of the power consumed doing work (watts) divided by the apparent power (volts-amperees). In direct current circuits, since...
there is no reversal of voltage or current, the power factor in effect is always unity. In alternating current circuits with lagging current (caused by inductive loads), the actual power available for work is the product of the volts times amperes times the power factor.

3. Electrical Formulas

The following basic formulas govern the relationship of voltage, amperage, and power in electrical circuits.

4. Apparent Power and Actual Power

The mathematical relationship between actual power and apparent power is shown by means of a vector diagram, Figure 5. The line AB is the reference point for voltage and measures the actual power. If the current is in phase with the voltage, then the apparent power is equal to the actual power, and the power factor is 1.0. This would be true of circuits with only resistive loads, such as electric heaters.

All inductive devices, such as motors, transformers, and solenoid coils require magnetizing current to create the magnetic field necessary for the device to operate. This magnetizing current, or reactive current as it is termed, does not produce usable power, but the effect of the magnetic field is to cause the current drawn from the power line to lag the voltage. The term reactive power is used to describe the product of the reactive current and the operating voltage, and is measured by line BC. The greater the reactive current, in proportion to the useful current, the greater the reactive power and the lower the power factor. The apparent power (volt-amperes) is measured by line AC. The symbol θ (theta) is conventionally used to denote the power factor angle.

Capacitors have a directly opposite effect to inductive magnetizing current and cause the current to lead the voltage rather than lag. As a result, capacitors installed in circuits with low power factors tend to cancel the effects of the reactive current and increase the power factor.

5. Effects of Poor Power Factor

Regardless of the actual power consumed, the electric distribution system sees volt-amperes. The presence of reactive current means the power supply lines must carry more current than that actually consumed by the load, and this additional current causes greater line losses, more voltage drop, and imposes a greater load on generators, transformers and distribution lines.

Generator and transformer output is measured in volt-amperes, so the greater the reactive current, the less actual (or usable) power the generator can produce and the transformer can handle. The combined effects of low power factor greatly increase the power company’s cost for capital equipment, so power companies frequently charge penalties for low power factors.

The reasons for this are that power companies must be prepared to satisfy normal transmission line (I^2R) losses caused by low power factor and also increase generating capacity to provide apparent power. As energy production costs rise and energy conservation becomes more important, it is probable that electrical specifications will increasingly call for power factor correction.
6. Calculating Power Factor Correction

The vector power diagram provides a convenient means of mathematically calculating power factor correction. Figure 6 diagrams an actual motor installation. The metric prefix “K” for kilo means 1000, so the actual power is 12 KW and the apparent power is 15 KVA.

The power factor by definition is actual power divided by apparent power, and is equal to .80.

To determine the reactive power, it is necessary to calculate a leg of the power factor triangle. As you will recall, the square of the hypotenuse (side opposite the right angle) is equal to the sum of the squares of the other two sides.

\[
\begin{align*}
(AC)^2 &= (AB)^2 + (BC)^2 \\
(BC)^2 &= (AC)^2 - (AB)^2 \\
(\text{Reactive Power})^2 &= (15)^2 - (12)^2 \\
\text{Reactive Power} &= \sqrt{225 - 144} \\
&= \sqrt{81} \\
&= 9 \text{ KVAR}
\end{align*}
\]

A kilovar (KVAR) is 1000 volt-amperes of reactive power. If sufficient capacitance is added to the circuit to produce 9 KVAR of leading reactive power, this will cancel the 9 KVAR of lagging reactive power created by the induction motor; the apparent power and actual power will become the same; and the power factor will be increased to 1.0.

7. Electric Motor Characteristics

Figure 7 (see following page) shows the motor performance curves for a typical three-phase induction motor. The only scales shown are for power factor and motor torque, but the remainder of the curves are shown for reference. All values other than torque are on a vertical scale.

Note that even with no load, and no power consumption, the motor continues to draw magnetizing current. Since this reactive magnetizing current is relatively constant, the power factor declines rapidly as the motor loading is reduced.

8. Dangers of Over-Correction

It is always possible to correct a motor to unity power factor, but total correction is normally not recommended. The influence of other reactive forces on the power line, such as changing motor or transformer load, is unpredictable, and if the power factor is over-corrected, it can cause high currents, high magnetic side pull forces on the motor rotor, high voltage, and transient motor over-torque much greater than full load motor torque. Whether overcorrection will cause motor damage is uncertain, but there is evidence that motor life can be shortened by voltage spikes caused by over-correction. A safer course is a more conservative one, limiting correction to the .9 (or 90%) level.

9. Calculating Kilovars of Power Factor Correction for Three-Phase Motors

Convenient Tables of power factor correction factors have been calculated to avoid the necessity for a laborious calculation for each application. Table 1 (following pages) gives multipliers to be used to determine the capacitor kilovars required. The multiplier (or KK) to be used is found by locating the original power factor in the left hand column, and then reading the required value at the intersection of the original power factor row, and the desired corrected power factor. The required kilovars are then calculated as follows:

\[
\text{KVAR} = (KK) \times (\text{KW load})
\]

The original compressor power factor can easily be calculated from the compressor specification sheet.

The equation for three-phase power (from page 2) is:

\[
\text{Power (Watts)} = IE \times \text{PF} \times 1.73
\]
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<th>Original Power Factor</th>
<th>Corrected Power Factor</th>
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</table>

Table 1
KW Multipliers to Determine Capacitor Kilovars Required for Power Factor Correction
Therefore, power factor can be calculated by:

\[ PF = \frac{P}{IE \times 1.73} \]

Example:

Determine the kilovar correction necessary to increase the power factor to 90% for a 25 H.P., 460 volt, high temperature compressor operating at 45° evaporator and 120°F condensing temperature.

(a) From a typical specification sheet, the compressor power input is 23,400 watts and the amperage draw is 36.5 amps.

(b) \[ PF = \frac{P}{IE \times 1.73} = \frac{23,400}{36.5 \times 460 \times 1.73} = .81 \]

(c) From Table 1, the required multiplier, or \( K_k \), is .240

(d) KVAR correction = .240 x 23,400 = 5.6 KVAR

A similar equation from page 2 may be used to determine single-phase KVAR. For any given application, the kilovars required for power factor correction are determined by the operating condition selected as a basis for correction and the amount of correction desired.

10. Kilovars Required for Power Factor Correction For Selected Copeland® Compressors

The normal operating power factor is based on operating data at the following selected application conditions:

High Temperature
45°F evaporating temperature
130°F condensing temperature

Medium Temperature
20°F evaporating temperature
120°F condensing temperature

Low Temperature
-25°F evaporating temperature
110°F condensing temperature

Two-Stage Ultra-Low Temperature
-50°F. evaporating temperature
110°F. condensing temperature

11. Kilovars vs. Capacitors

In the basic power factor vector diagram, the reactive power required for correction is calculated as “volt amperes reactive,” commonly referred to as KVAR of kilovars, a unit of 1,000 volt-amperes in reactive power. While the actual electrical components used to obtain the power factor corrections are capacitors, manufacturers sell kits consisting of pre-wired capacitors in assemblies in terms of kilovars.

It is possible to calculate the size of capacitors that must be used for power factor correction. The mathematical and electrical relationships are described by the following formulas:

\[ C = \frac{3 \times I_L}{f \times V_L} \times K_c \]

\[ C = \frac{I_L}{f \times V_L} \times K_c \]

In All Cases:

\[ K_c = \frac{K_K \times PF_1 \times 10^6}{2 \times \pi \sqrt{3}} \]

\[ C = \text{Capacitance in microfarads} \]
\[ I_L = \text{Line current in amperes} \]
\[ f = \text{Frequency in hertz} \]
\[ V_L = \text{Line voltage} \]
\[ \sqrt{3} = 1.732 \]
\[ K_K = \text{Multiplier from Table 1} \]
\[ PF_1 = \text{Original power factor} \]
\[ K_C = \text{Factor for calculating capacitor size} \]
\[ \pi = 3.1416 \]

For convenience, the \( K_c \) factor has been calculated and is shown in Table 2 (following page) for various power factor corrections.

For single-phase loads, the capacitor must be connected across the line ahead of the motor. For three-phase loads, the value determined is for a single capacitor, three being required, connected line to line. See Figure 8 (following pages). Capacitors should be oil filled, and the capacitor rated voltage should be in excess of maximum line voltage.
Table 2

$K_c$ Factor for Use in Calculating Capacitor Size for Power Factor Correction

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12. Calculating Capacitors for Power Factor Correction

The following examples illustrate the calculations necessary to select capacitors for power factor correction.

Example 1. Single Phase
Determine the capacitance required to correct the power factor to 85% for a small single-phase motor operating with a 72% power factor, drawing 865 watts and 10.44 amperes on 115 volt, single-phase, 60 hertz power.

\[
C = \frac{3 \times I_L}{f \times V_L} \times K_C
\]

\[
= \frac{1.732 \times 10.44}{60 \times 115} \times 22760
\]

\[
= 59.6 \text{ MFD}
\]

Use a 60 MFD capacitor across the line.

Example 2. Three-Phase
Determine the capacitance required to correct the power factor to 90% for a three-phase motor operating with a 77% power factor, drawing 7440 watts and 14.7 amperes on 380 volt, three-phase, 50 hertz power.

\[
C = \frac{I_L}{f \times V_L} \times K_C
\]

\[
= \frac{14.7}{50 \times 380} \times 24410
\]

\[
= 18.9 \text{ MFD}
\]

Use three 20 MFD capacitors, across the line, one for each phase.

13. Kilovars vs. Capacitors Three-Phase Motors

It is possible to make a direct calculation of the relationship between a correction in kilovars and the capacitors necessary to create the kilovar correction. Copelan2d1 -91-2122249

The basic formula for three-phase motors is:

\[
C = \frac{1000 \times \text{KVAR}}{6 \times \pi \times f \times (KV)^2}
\]

\[KV = \text{Kilovolts}\]
In the three-phase example above, the kilovar factor KK, from Table 1, for a correction from 77% to 90% would be .345. Therefore, the kilovar correction required would be .345 x 7.44 KW = 2.57 KVAR.

To convert this value to capacitance

\[
C = \frac{1000 \times \text{KVAR}}{6 \times \pi \times f \times (\text{KV})^2} = \frac{1000 \times 2.57}{6 \times 3.1416 \times 50 \times (.38)^2} = 18.9 \text{ MFD as in example 2}
\]

14. Installation of Power Capacitors

A large bank of capacitors installed on the line side for correction of a group of compressors carries the danger of over-correction should some of the compressors be cycled off. Proper control may require sophisticated and elaborate control equipment. The simplest and most effective installation is to connect the correction capacitors to the load side of the contactor, so that the capacitor correction and the motor are switched simultaneously in and out of the circuit. No complicated engineering studies are needed, and the compressor is fully protected against over-correction.

Capacitors used for power factor correction can be connected either in wye or in delta. The decision will depend on the overall economics, availability of units and total KVAR required.

For example, in Figure 9 three 15KVAR capacitors are connected in wye, the result would be a total KVAR of 15.

\[
\text{Wye Bank} = (3)(15) \left( \frac{460/\sqrt{3}}{460} \right)^2
\]

Wye bank = 45 (.3333) = 15 KVAR

Now consider the same 15 KVAR capacitors connected in delta. The total KVAR is:

\[
\text{Delta Bank} = (3)(15).
\]

Delta Bank = 45 KVAR.

The most critical application of capacitors for power factor correction is on motors using two contactors (part winding start), multi speed, or perhaps dual voltage. Some Copeland brand compressors may use part winding start connections and extreme caution must be used when applying power factor correction.

A part winding start connection as shown below is basically a transformer and when capacitors are connected to each set of windings, a circuit is completed and circulating currents begin to flow when power is applied. There is a time delay of approximately 1 second between the contactors and the chances that voltages are in phase when the second contactor closes are unlikely. This results in high transient currents and could produce torques 20 to 30 times normal. For a compressor under load, this could result in broken rods and/or broken crank shafts.

A special contactor arrangement should be considered to disconnect the capacitors from the de-energized winding during start or bring on the required KVAR after the compressor is operating.

15. Summary

Power factor correction is a mixed blessing. If not accomplished in an approved manner, it may affect compressor reliability. Power factor correction should be made only if absolutely necessary on two contactor or part-winding start compressor applications, and care must be taken to avoid overcompensation under all operating conditions.

Remember: power factor correction does not decrease the power consumed by the motor, and on small compressors, power factor correction may not be economically justifiable.
Motor/Compressor for Part Winding Start

Figure 10.
Without Power Factor Correction

Figure 11.
With Power Factor Correction

Induced Voltage
Open Circuit

Induced Voltage
Closed Circuit
Circulating Currents