



Subject Total Power Factor

File General

Preface — In this product data, it is intended to explain power factor in a simplified manner for all conditions. Vector illustrations are shown to represent complex mathematical expressions. This method is used primarily to aid in understanding this subject.

Introduction

The subject of total power factor is frequently misunderstood and commonly ignored — especially when dealing with electrical installations employing power semiconductors. An understanding of total power factor, when it might present a problem, its ill effects, and corrective action, can be important considerations when applying solid state controllers such as adjustable frequency and phase back (SCR) controllers. These subjects will be reviewed in this product data.

Summary

For electrical installations with standard contactor type controllers (Figure 1), the ill effects of a poor power factor can be improved with conventional techniques using power factor capacitors or synchronous motors. No other considerations are usually necessary.

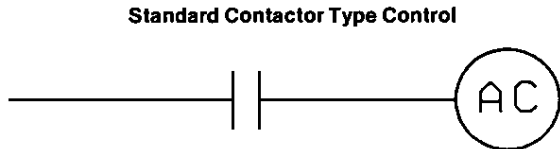


Figure 1

For electrical installations with controllers using phase back power semiconductors (SCR's) such as dc adjustable voltage or ac adjustable voltage (Figure 2), the complete installation should be evaluated before applying capacitors for power factor improvement. This is recommended in order to determine if excessive currents will be generated that might damage electrical equipment in the distribution system, such as distribution transformers, etc. Appropriate apparatus can then be applied to prevent this.

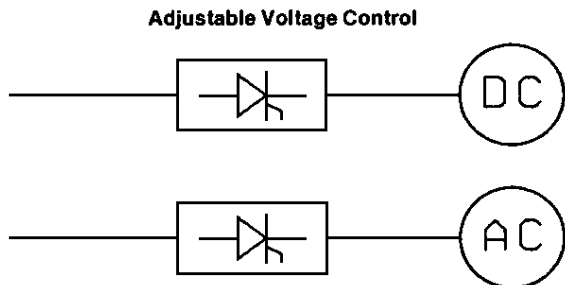


Figure 2

For electrical installations with adjustable frequency controllers having a rectifier (diode) front end (Figure 3), a high power factor will normally exist. Capacitors should not be required to improve power factor.

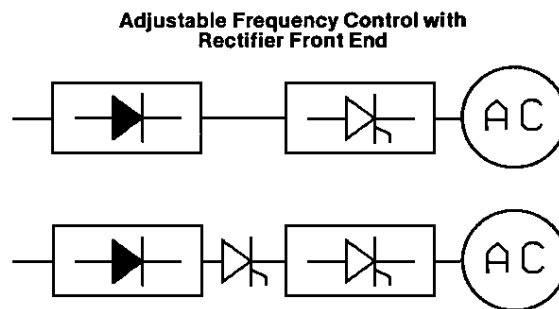


Figure 3

For electrical installations with adjustable frequency controllers having an SCR front end (Figure 4), power factor capacitors might be applied should the ill effects of a poor power factor become significant. In these cases, the complete installation should be evaluated first to determine if excessive harmonic currents will be generated that might damage electrical equipment in the distribution system. Appropriate apparatus can then be applied to prevent this.

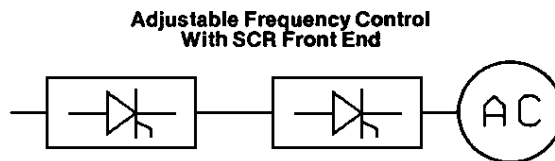


Figure 4

For examples illustrated in Figures 2 and 4, the possibility of damaging electrical equipment in a distribution system is caused by two simultaneous phenomena: harmonic currents generated as a result of using phase controlled power semiconductors (SCR's), and the application of capacitors to improve power factor. A more detailed explanation of these phenomena will be given later.

Power Factor Description

The conventional explanation of power factor assumes a pure sine wave for current and voltage. This is usually associated with installations having contactors and no power semiconductors. In these cases, power factor is defined as the ratio of active or real power (KW) to the apparent power (KVA). The difference in KW and KVA is caused by inductance (reactive element) in the system from transformers, motors, etc.

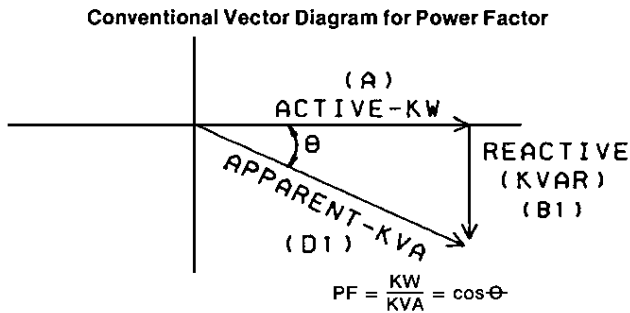


Figure 5

Reactive Element

In Figure 5, the total apparent power KVA (D₁) is the vector sum of active component (A) and reactive element (B₁). The ratio of vector A and vector D₁ is cosine of angle θ, which is the familiar expression for power factor. This expression is not valid when the wave forms are distorted, except when considering only the fundamental components of voltage and current. This is reviewed later. Power factor angle θ represents a phase shift or displacement between voltage and current when pure sinusoidal (undistorted) wave forms exist. Typical wave forms are illustrated in Figure 6.

Typical Wave Form Showing Lagging Current

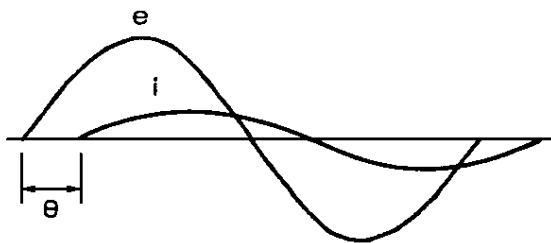


Figure 6

For a purely resistive circuit, referring to Figures 5 & 6, there is no reactive element. The voltage and current are in phase, angle θ is then zero (cosine θ = 1), and power factor is unity.

As the reactive element increases for a highly inductive or capacitive circuit, the current will lag or lead the voltage, and angle θ will approach 90°. In these cases, the power factor approaches zero.

Power factor can be considered as a measure or indication of the efficiency of an electrical distribution system. When power factor approaches zero, it is considered poor. Poor power factor results in certain ill effects for an installation. These are generally classified as follows:

- Wasted capacity in a distribution system
- Additional power losses in the system
- Additional voltage drop in the system
- Power company penalty

The reactive element of a motor's inductance can be measured with a power factor meter and can be reduced by applying power factor capacitors. This will improve the power factor for an installation and minimize ill effects.

Total Power Factor

When power semiconductors are employed in an electrical installation, power factor acquires a new dimension; and another ill effect (equipment failures) can be

possible under certain conditions. The addition of capacitors to improve power factor may be more detrimental than corrective. This requires that the installation be evaluated first.

In the conventional explanation of power factor previously described, only two components of power contribute to the total KVA: the active component and the reactive element. When power semiconductors are used in an installation, total power factor then becomes a three-dimensional quantity consisting of:

- A. Active or Real Component** — This component is the real power consumed to produce torque in a motor, usually expressed in KW.
- B. Displacement Component** — This component consists of two elements: a reactive element and a phase control element. The reactive element, described in a previous paragraph, produces flux for the motor. The phase control element is present only when phase controlled type power semiconductors are used, such as SCR's. This displacement component is power not consumed when producing torque in a motor and is usually expressed in KVAR's.
- C. Harmonic Component** — This component is present when any type of power semiconductors are used, such as SCR's or simple rectifiers. Generally, the harmonic component does not produce useful torque in a motor and is not present with contactor control having pure sinusoidal voltage and current.

In Figure 7, the total apparent power (D) is the three-dimensional vector sum of the three components (A), (B) and (C) described above, when they exist. The active and displacement components are shown on the X and Y axes, as commonly illustrated. The harmonic component is on the Z axis in the third dimension. This concept of a three-dimensional vector sum requires a complex mathematical derivation which is beyond the scope of this explanation.¹

Three-Dimensional Vectors for Total Apparent Power

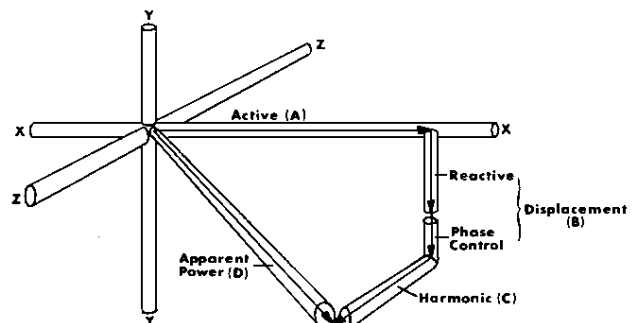


Figure 7

When power semiconductors are used in a circuit, total apparent power (D) includes the harmonic component (C), and the displacement component (B) which may or may not include the phase control element (Figure 7). In these cases, total power factor is the ratio of active component (A) to total apparent power (D). The following brief review of harmonics is given to aid in understanding an explanation of the displacement and harmonic components.

Reference

¹The Fundamental Theory of Arc Converters — H Rissik. Universal Microfilms, Inc., Ann Arbor, London. Chapman & Hall Ltd. 1939. Pages 85 to 96.

Harmonics

Any distorted sine wave can be subdivided into its fundamental frequency component and various harmonic frequency components. For a 60 Hertz fundamental frequency, the second harmonic would be 120 Hertz, third harmonic would be 180 Hertz, etc. The amplitude and frequency of the fundamental and the specific harmonic frequencies are the function of the type of distorted wave. As an example, the distorted sine wave illustrated in Figure 8 will not have a second, third or fourth harmonic, but will have higher order of harmonics such as the fifth, seventh, and others.

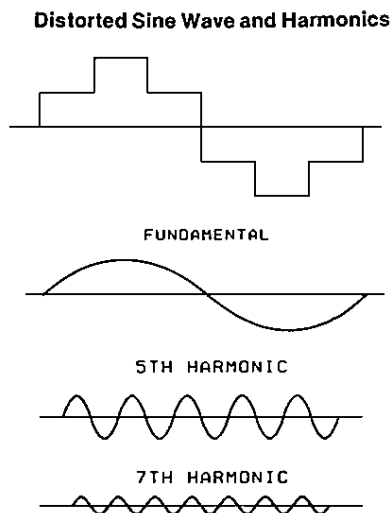


Figure 8

Displacement Component

The displacement component illustrated in Figure 7, consisting of the reactive and phase control elements, deals only with pure sinusoidal (undistorted) current and voltage wave forms. When distorted sinusoidal current or voltage exists, only the fundamental component is considered as shown in Figure 8. The reactive element is the same as described previously for power factor.

The phase control element is caused by the delay of current flow with respect to voltage when using phase controlled type power semiconductors (SCR in Figure 9). When the distorted current wave (i) is subdivided into its fundamental and harmonic frequencies, the fundamen-

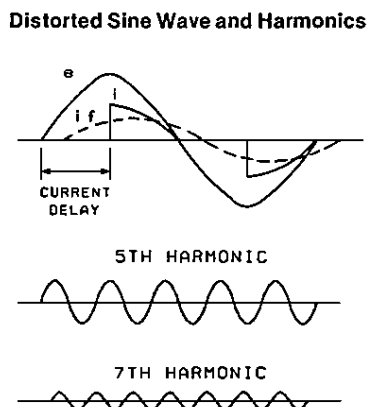


Figure 9

tal current (i_f) will lag the voltage (e) similar to the lagging current illustrated in Figure 6. Hence, this fundamental of pure sinusoidal current will produce an element of displacement power similar to that produced with inductance in a circuit. As the current delay is increased (phasing back current flow), the phase control element will increase, resulting in a lower power factor.

The phase control effect is not accurately measurable with power factor meters but can be observed with an oscillographic display. This element along with the reactive element can be corrected with power factor capacitors as the current delay is increased. *However, before applying capacitors to improve power factor when SCR's are in the circuit, there should be a thorough evaluation of the total distribution system to avoid abnormally high currents that can cause equipment failures.* This is described in the next paragraph "Harmonic Component".

Harmonic Component

This component is caused by distorted sinusoidal current or voltage wave forms when any type of power semiconductor is used in a circuit, such as SCR's or simple rectifiers. The "harmonic component" deals with the harmonic frequencies generated by a distorted sine wave; whereas, the "phase control" element described previously deals with only the fundamental frequency generated by the distorted sine wave.

In Figure 7, the total apparent power (D) can be measured with current and volt meters; but the total power factor with the harmonic component cannot be measured with a power factor meter. However, the harmonic component can be observed with a spectrum analyzer.

The harmonic component cannot be corrected by adding capacitors, as with the displacement component. As the harmonic component in a distribution system becomes larger, with respect to the total power, and when capacitors are added to improve the power factor, the magnitude of the harmonic currents at some frequencies may increase excessively due to resonance with system capacitance and inductance. As a result, the harmonic currents could overheat or damage equipment, such as transformers, lighting, etc., in the distribution system.

The ill effects of excessive harmonics can be corrected by designing a filter circuit which will suppress a specific harmonic frequency. These circuits usually consist of a tuning inductance designed to match the circuit capacitance for a specific resonant frequency. However, this filter will not completely eliminate the harmonic frequencies.

Displacement Power Factor

In general terms, power factor is defined as the ratio of watts to voltamps. Total power factor involves all components of power in a distribution system (Displacement and Harmonic). Because the harmonic component can vary dramatically during operation with changing conditions such as load and gating, and since it cannot be corrected with capacitors, total power factor is seldom used in specifications. For this reason, in practice, displacement power factor, which includes the displacement component but not the harmonic component, is usually specified.

In Figure 10, displacement power factor is the ratio of vector A to D_1 or D_2 is used for circuits with simple rectifiers (Figure 3) where there is only a small reactive element. D_2 is used for circuits with controlled rectifiers (SCR's) (Figures 2 & 4) where there is a reactive element and a phase control element. In both cases the displacement power factor can be reasonably estimated or calculated, but it cannot be easily measured.

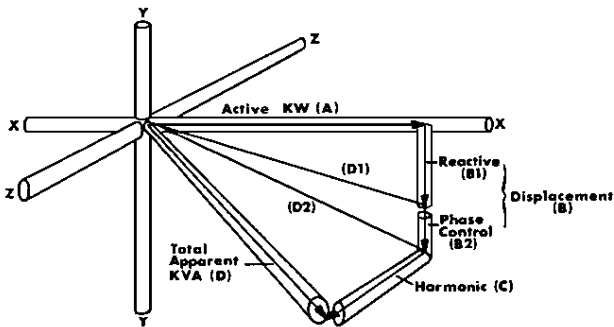


Figure 10

General Information on Power Factor

The total power factor of an electrical distribution system can be influenced by several parameters, such as inductance in the distribution system, controller designs, motor designs, load conditions and speed conditions. Each of these subjects is reviewed below.

Controller Designs and Speed Conditions

With conventional contactor type controllers (Figure 1), total power factor is the same as the displacement power factor which is reflected to the distribution system. It is usually related to the motor design and load condition. Normally, the speed condition is not a factor with squirrel cage motors which do not operate continuously at reduced speed with contactor control.

With controllers using phase control type power semiconductors (SCR in Figure 2), the total power factor reflected to the distribution system is usually related to the motor design, load condition and speed condition. In these cases, the total power factor will change significantly between full speed and reduced speed. If power factor capacitors are used to improve the displacement component at reduced speed, a condition could be created to increase harmonic currents and possibly cause equipment failures in the distribution system. This subject was discussed under "Harmonic Component".

With adjustable frequency control, the dc link in the controller provides an isolation medium between the motor and the distribution system. Consequently, total power factor reflected to the distribution system will not be influenced by the motor design or load condition. However, with certain types of inverter designs, a reduced speed condition could result in a poor total power factor reflected to the distribution system.

For inverter designs with rectifier (diodes) for the front end (Figure 3), the inverter will reflect a relatively high total power factor to the distribution system. The speed condition should not be a factor. Normally, it should not be necessary to apply power factor capacitors in these cases.

For inverter designs using controlled rectifiers (SCR's) for the front end (Figure 4), total power factor may be a consideration as the frequency (speed) is reduced. Should power factor capacitors be applied to improve the displacement component, they should always be applied on the line side of the inverters and not at the motor terminals. When capacitors are used in these cases, a condition could be created to increase harmonic currents and possibly cause equipment failures in the distribution system. This subject was discussed under "Harmonic Component".

Motor Design

The reactive element of displacement power factor reflected at a motor's terminals is a function of the induc-

tance in the motor. Some motors, such as low speed motors, by design may require a higher percentage of magnetizing current than others. Consequently, these will reflect a lower displacement power factor at the motor terminals. With inverter control, this power factor is reflected only to the controller load side and not the distribution system.

Load Condition

The displacement power factor reflected at a motor's terminals is a function of the motor load also. With inverter control, this power factor is reflected only to the controller load side and not the distribution system.

Referring to Figure 11, the active component at light load will be less than at full load. However, the reactive element will remain the same, causing the power factor angle θ to increase. This results in a lower power factor and less total current. This condition can be improved with control techniques responsive to power factor which cause the reactive element to be reduced at light load, thus resulting in minimizing the current to the motor.

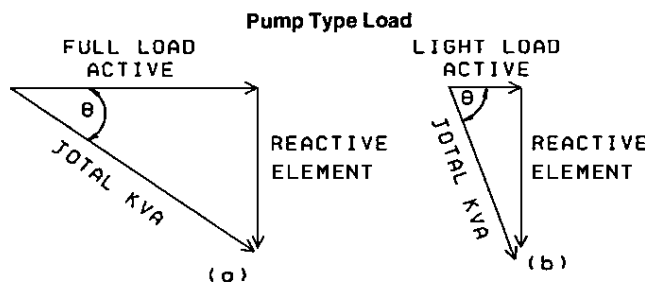


Figure 11

The importance of power factor with regard to loading is often misunderstood. For some installations, a load with a high power factor may be more detrimental than a load with a lower power factor. The magnitude of the total KVA demand in the distribution system may be the important consideration, and not always the power factor number itself. This is especially true with pump and fan type loads at reduced speed. Figure 11 illustrates this condition.

In Figure 11a, for a pump at full speed (full load), the power factor angle θ is relatively small, indicating a high power factor. However, the total KVA demand for the installation is relatively large. Based on penalties for a low power factor, this could be the best case.

In Figure 11b, for a pump at reduced speed (light load), the power factor angle θ is relatively large, indicating a poor power factor. However, the total KVA demand for the installation is relatively small. Based on penalties for KVA demand, this could be the best case.

Conclusion

The difference between total power factor and displacement power factor should be recognized. Displacement power factor is commonly specified by manufacturers, but does not include the harmonic component in the system KVA. The harmonic component can be significant with controllers using power semiconductors. This depends on the degree of sine wave distortion with a particular control. When power factor capacitors are used with controllers having power semiconductors, the complete distribution system should be evaluated to determine whether or not tuning inductors are required to limit harmonic currents.