

POWER FACTOR CORRECTION

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.

1 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" (volt-amperes), 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-amperes). 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.

2 Electrical Formulas

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

Direct Current	Single-phase Alternating Current	Three-Phase Alternating Current
$I = U/R$	$I = U/R$	$I = U/R$
$U = IR$	$U = IR$	$U = IR$
$P = UI$	$P = UI \cos \phi$	$P = UI \cos \phi \sqrt{3}$
$P = RI^2$	$P = RI^2 \cos \phi$	$P = RI^2 \cos \phi \sqrt{3}$
$VA = UI$	$VA = UI$	$VA = UI \sqrt{3}$

U = Voltage
I = Current
R = Resistance
 $\cos \phi$ = Power factor

3 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.

3.1 Effect 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.

3.2 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. Therefore,

$$(AC)^2 = (AB)^2 + (BC)^2$$

$$(BC)^2 = (AC)^2 - (AB)^2$$

$$(\text{Reactive Power})^2 = (15)^2 - (12)^2$$

$$\text{Reactive Power} = \sqrt{(225-144)} = \sqrt{81} = 9 \text{ kVAR}$$

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.

3.2.1 Electric Motor Characteristics

Figure 7 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.

3.2.2 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.

3.2.3 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 gives multipliers to be used to determine the capacitor kilovars required. The multiplier (or K_K) 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:

$$\text{kVAR} = (K_K) \times (\text{kW load})$$

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

The equation for three-phase power (from page 1) is:

$$\text{Power (Watts)} = UI \cos \phi \sqrt{3}$$

Therefore, power factor can be calculated by:

$$\cos \phi = P / (UI\sqrt{3})$$

Example:

Determine the kilovar correction necessary to increase the power factor to 90% for a ZR16K3E-TWD, 400 V, 50 Hz., high temperature compressor operating at ARi Point (evap = 7.7°C cond = 54.4).

- a) From a typical specification sheet, the compressor power input is 11400 Watt and the amperage draw is 19.12 Amps
- b) $\cos \phi = P / (UI\sqrt{3}) = 11400 / (400 \times 19.12 \times 1.73) = 0.86$
- c) From table 1, the required multiplier, or K_K , is 0.109
- d) $\text{KVAR correction} = 0.109 \times 11400 = 1.24 \text{ kVAR}$

A similar equation from page 1 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.

The power factor and correction required can vary greatly when the compressor operates outside of ARi conditions.

4 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 or kilovars, a unit of 1000 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:

Single Phase Motors

$$C = \frac{\sqrt{3} I_L}{f V_L} K_C$$

Three Phase Motors

$$C = \frac{I_L}{f V_L} K_C$$

In all cases

$$K_C = \frac{K_K \cos \phi_1 10^6}{2 \pi \sqrt{3}}$$

C = Capacitance in μF (microfarads)

I_L = Line current in Amp.

f = Frequency in Hz

V_L = Line voltage

K_K = Multiplier from table

$\cos \phi_1$ = Original power factor

K_C = Factor for calculating capacitor size

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. Capacitors should be oil filled, and the capacitor rated voltage should be in excess of maximum line voltage.

4.1 Calculating Capacitors for Power Factor Correction

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

4.1.1 Example 1. Single Phase

Determine the capacitance required to correct the power factor to 90% for a small single-phase motor operating with a 81% power factor, drawing 780 watts and 4.2 amperes on 230 volt, single-phase, 50 hertz power.

$$C = \frac{\sqrt{3} I_L}{f V_L} K_C = \frac{1.732 \times 4.2}{50 \times 230} \times 17863 = 11.3 \mu\text{F}$$

Use a 12 μF capacitor across the line.

4.1.2 Example 2. Three-Phase

Determine the capacitance required to correct the power factor to 90% for a three-phase motor operating with a 80% power factor, drawing 12600 watts and 22.8 amperes on 400 volt, three-phase, 50 hertz power.

$$C = \frac{I_L}{f V_L} K_C = \frac{22.8}{50 \times 400} \times 19496 = 22.2 \mu\text{F}$$

Use three 25 MFD capacitors, across the line, one for each phase.

4.2 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.

The basic formula for three-phase motors is:
(Delta connection)

$$C = \frac{1000 \times \text{KVAR}}{6 \pi f (\text{KV})^2} \quad \text{KV} = \text{Kilovolts}$$

In the three-phase example above, the kilovar factor K_K , from Table 1, for a correction from 80% to 90% would be 0.266. Therefore, the kilovar correction required would be $0.266 \times 12.6 \text{ KW} = 3.35 \text{ KVAR}$.

To convert this value to capacitance

$$C = \frac{1000 \times \text{KVAR}}{6 \pi f (\text{KV})^2} = \frac{1000 \times 3.35}{6 \pi \times 50 \times (0.40)^2} = 22.2 \mu\text{F} \text{ (as in example 2)}$$

Note: For capacitor connection in "Star", the capacitor value will be multiplied by 3: $C_{\text{STAR}} = 3 \times C_{\text{DELTA}}$ and the rated voltage divided by $\sqrt{3}$.

4.3 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.

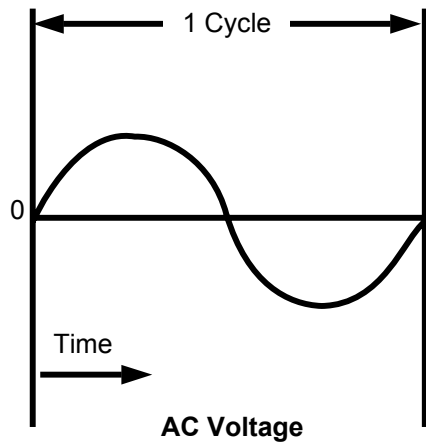
The simplest and most effective installation is to connect the correction capacitors to the load side of the contactor, so that the capacitor correction and the motor are switched simultaneously in and out of the circuit. No complicated engineering studies are needed, and the compressor is fully protected against over-correction.

The most critical application of capacitors for power factor correction is on motors using two contactors for part-winding start. There is no uniformity of opinion as to the best means of application. Basically a compressor with dual windings applied with two contactors is connected as though two separate motors are operating independently in parallel. To avoid overcompensation when the first half of the motor is energized, the KVARs of correction should be split, with one half connected to the load side of each contactor.

5 Summary

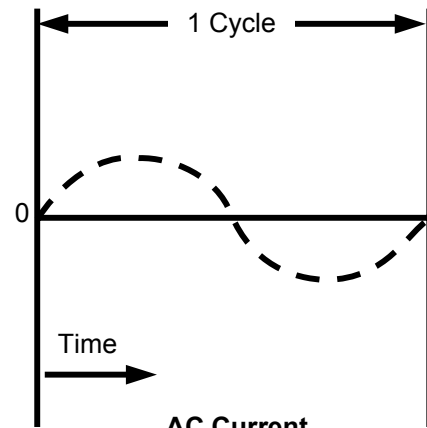
Power factor correction is a mixed blessing. If not accomplished in an approved manner, it may affect compressor reliability. Power factor correction should be made only if absolutely necessary on two contactor or part-winding start compressor applications, and care must be taken to avoid overcompensation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



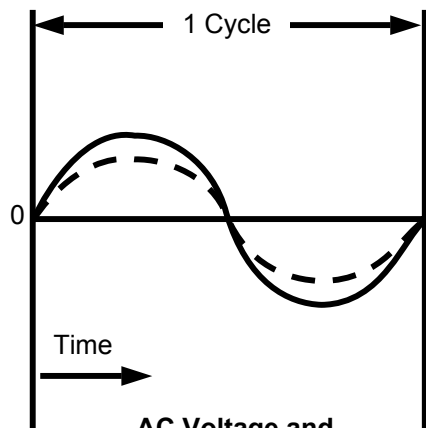
AC Voltage

Figure 1



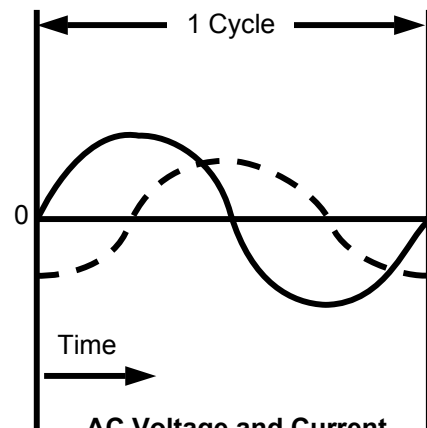
AC Current

Figure 2



**AC Voltage and
Current in Phase**

Figure 3



**AC Voltage and Current
out of Phase**

Figure 4

Sine Wave Representation of AC Voltage and Current

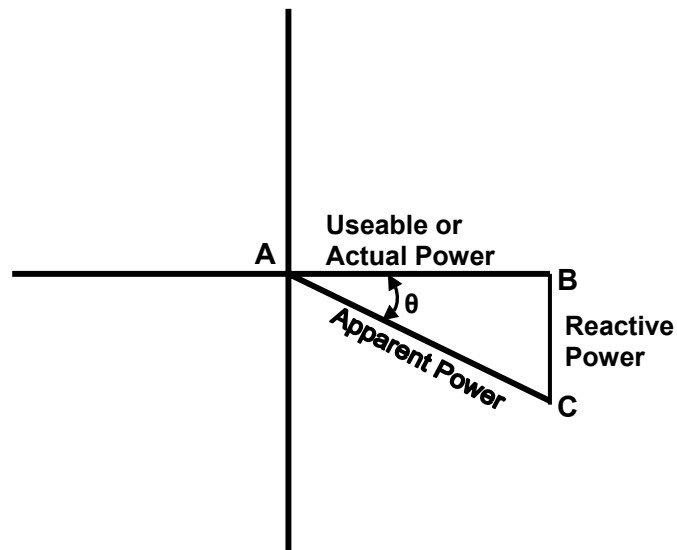


Figure 5. Vector Diagram Showing Lagging Power Factor

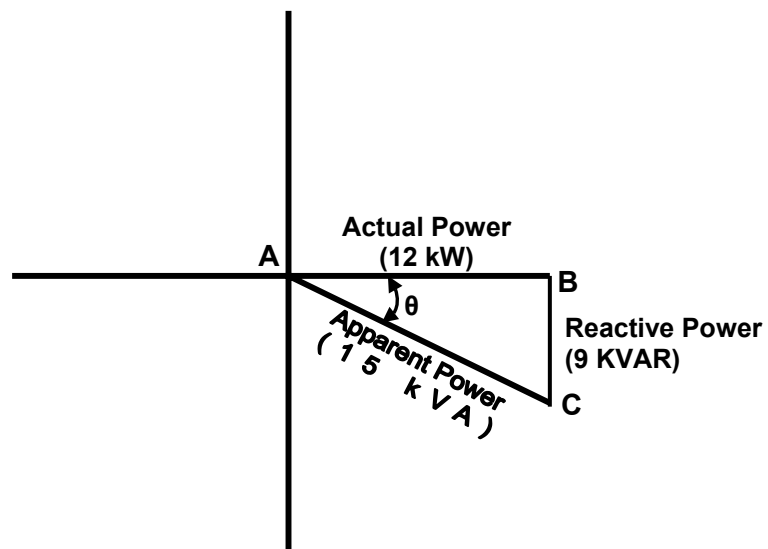


Figure 6. Vector Diagram For Calculating Power Factor Correction

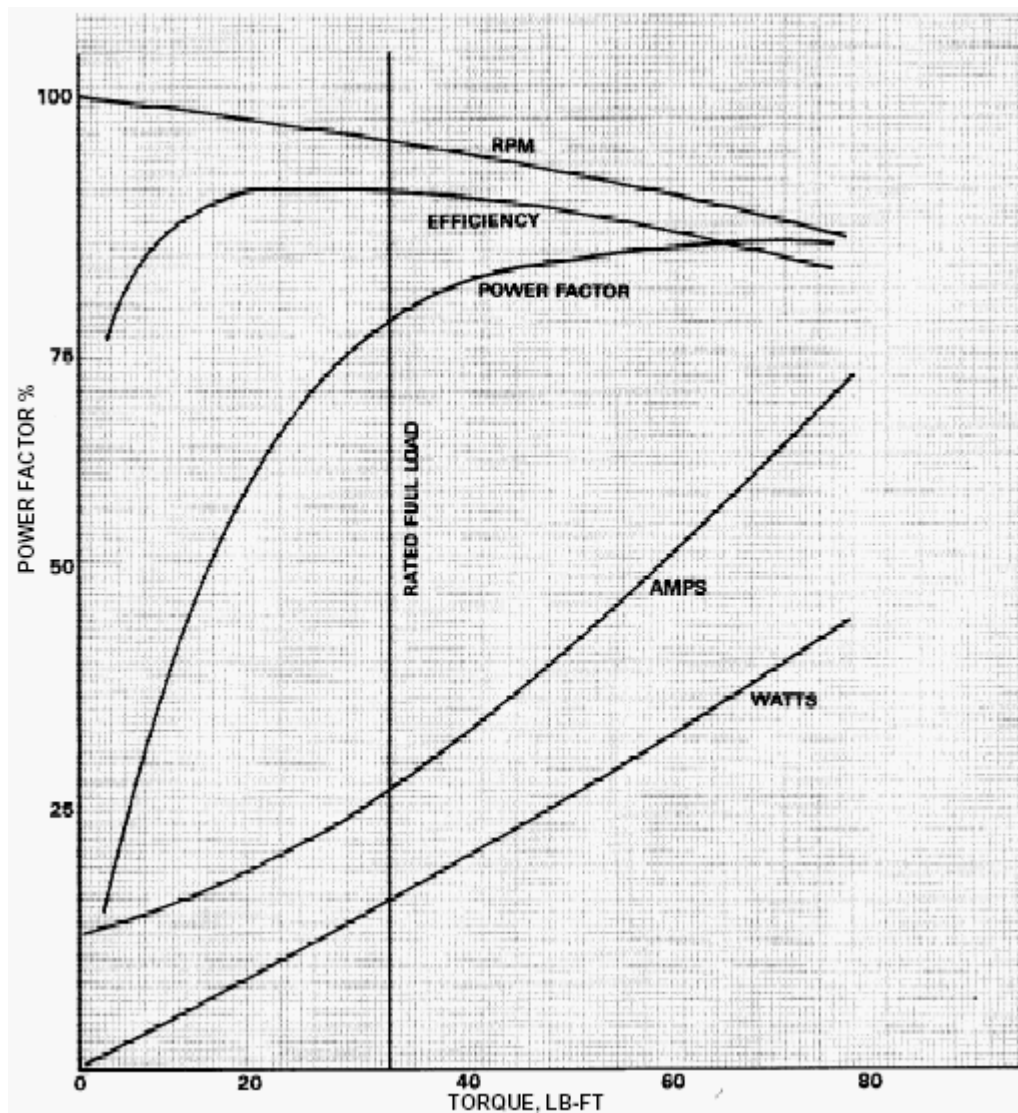


Figure 7

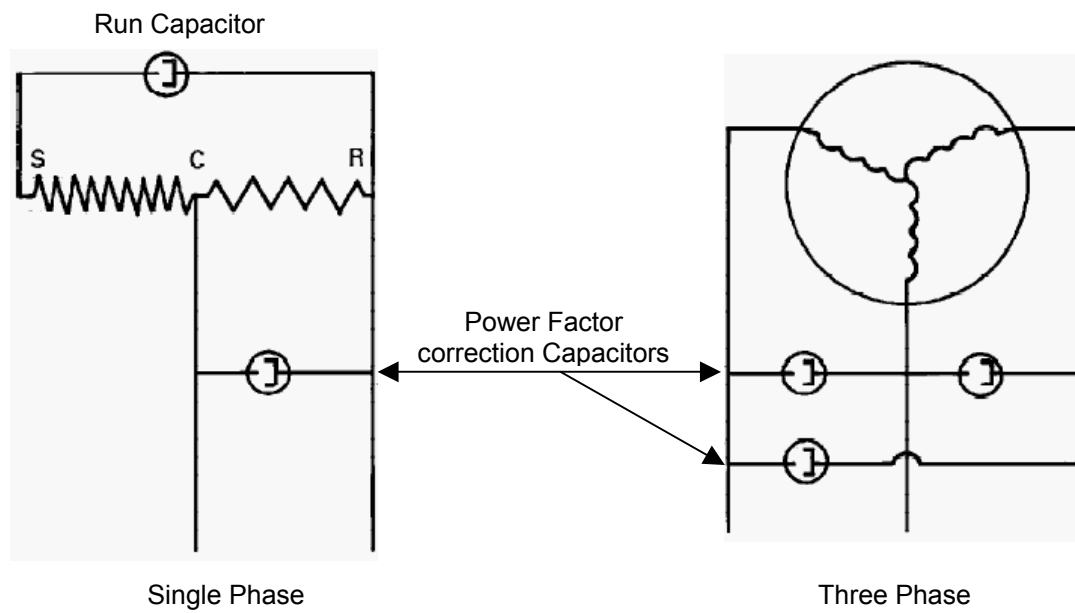


Figure 8. Installation Of Capacitors For Power Factor Correction

Table 1. kW Multipliers (K_K) to determine capacitor kilovars required for Power-factor correction

		Corrected Power factor ($\cos \phi$)															
		0.80	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95
Original Power Factor ($\cos \phi$)	0.50	0.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.306	1.337	1.369	1.403
	0.51	0.937	0.963	0.989	1.015	1.041	1.067	1.093	1.120	1.147	1.174	1.202	1.231	1.261	1.291	1.324	1.358
	0.52	0.893	0.919	0.945	0.971	0.997	1.023	1.049	1.076	1.103	1.130	1.158	1.187	1.217	1.247	1.280	1.314
	0.53	0.850	0.876	0.902	0.928	0.954	0.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271
	0.54	0.809	0.835	0.861	0.887	0.913	0.939	0.965	0.992	1.019	1.046	1.074	1.103	1.133	1.163	1.196	1.230
	0.55	0.768	0.794	0.820	0.846	0.873	0.899	0.925	0.952	0.979	1.006	1.034	1.063	1.092	1.123	1.156	1.190
	0.56	0.729	0.755	0.781	0.807	0.834	0.860	0.886	0.913	0.940	0.967	0.995	1.024	1.053	1.084	1.116	1.151
	0.57	0.691	0.717	0.743	0.769	0.796	0.822	0.848	0.875	0.902	0.929	0.957	0.986	1.015	1.046	1.079	1.113
	0.58	0.655	0.681	0.707	0.733	0.759	0.785	0.811	0.838	0.865	0.892	0.920	0.949	0.979	1.009	1.042	1.076
	0.59	0.618	0.644	0.670	0.696	0.723	0.749	0.775	0.802	0.829	0.856	0.884	0.913	0.942	0.973	1.006	1.040
	0.60	0.583	0.609	0.635	0.661	0.687	0.714	0.740	0.767	0.794	0.821	0.849	0.878	0.907	0.938	0.970	1.005
	0.61	0.549	0.575	0.601	0.627	0.653	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.873	0.904	0.936	0.970
	0.62	0.515	0.541	0.567	0.593	0.620	0.646	0.672	0.699	0.726	0.753	0.781	0.810	0.839	0.870	0.903	0.937
	0.63	0.483	0.509	0.535	0.561	0.587	0.613	0.639	0.666	0.693	0.720	0.748	0.777	0.807	0.837	0.870	0.904
	0.64	0.451	0.477	0.503	0.529	0.555	0.581	0.607	0.634	0.661	0.688	0.716	0.745	0.775	0.805	0.838	0.872
	0.65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.714	0.743	0.774	0.806	0.840
	0.66	0.388	0.414	0.440	0.466	0.492	0.519	0.545	0.572	0.599	0.626	0.654	0.683	0.712	0.743	0.775	0.810
	0.67	0.358	0.384	0.410	0.436	0.462	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.682	0.713	0.745	0.779
	0.68	0.328	0.354	0.380	0.406	0.432	0.459	0.485	0.512	0.539	0.566	0.594	0.623	0.652	0.683	0.715	0.750
	0.69	0.299	0.325	0.351	0.377	0.403	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.623	0.654	0.686	0.720
	0.70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.565	0.594	0.625	0.657	0.692
Original Power Factor ($\cos \phi$)	0.71	0.242	0.268	0.294	0.320	0.346	0.372	0.398	0.425	0.452	0.480	0.508	0.536	0.566	0.597	0.629	0.663
	0.72	0.214	0.240	0.266	0.292	0.318	0.344	0.370	0.397	0.424	0.452	0.480	0.508	0.538	0.569	0.601	0.635
	0.73	0.186	0.212	0.238	0.264	0.290	0.316	0.343	0.370	0.396	0.424	0.452	0.481	0.510	0.541	0.573	0.608
	0.74	0.159	0.185	0.211	0.237	0.263	0.289	0.316	0.342	0.369	0.397	0.425	0.453	0.483	0.514	0.546	0.580
	0.75	0.132	0.158	0.184	0.210	0.236	0.262	0.289	0.315	0.342	0.370	0.398	0.426	0.456	0.487	0.519	0.553
	0.76	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.288	0.315	0.343	0.371	0.400	0.429	0.460	0.492	0.526
	0.77	0.079	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.289	0.316	0.344	0.373	0.403	0.433	0.466	0.500
	0.78	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.263	0.290	0.318	0.347	0.376	0.407	0.439	0.474
	0.79	0.026	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.264	0.292	0.320	0.350	0.381	0.413	0.447
	0.80	0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.238	0.266	0.294	0.324	0.355	0.387	0.421
	0.81		0.000	0.026	0.052	0.078	0.104	0.131	0.157	0.184	0.212	0.240	0.268	0.298	0.329	0.361	0.395
	0.82			0.000	0.026	0.052	0.078	0.105	0.131	0.158	0.186	0.214	0.242	0.272	0.303	0.335	0.369
	0.83				0.000	0.026	0.052	0.079	0.105	0.132	0.160	0.188	0.216	0.246	0.277	0.309	0.343
	0.84					0.000	0.026	0.053	0.079	0.106	0.134	0.162	0.190	0.220	0.251	0.283	0.317
	0.85						0.000	0.026	0.053	0.080	0.107	0.135	0.164	0.194	0.225	0.257	0.291
	0.86							0.000	0.027	0.054	0.081	0.109	0.138	0.167	0.198	0.230	0.265
	0.87								0.000	0.027	0.054	0.082	0.111	0.141	0.172	0.204	0.238
	0.88									0.000	0.027	0.055	0.084	0.114	0.145	0.177	0.211
	0.89										0.000	0.028	0.057	0.086	0.117	0.149	0.184
	0.90											0.000	0.029	0.058	0.089	0.121	0.156
	0.91												0.000	0.030	0.060	0.093	0.127
	0.92													0.000	0.031	0.063	0.097
	0.93														0.000	0.032	0.067
	0.94															0.000	0.034
	0.95																0.000

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