## TSEWG TP-2:   CAPACITORS FOR POWER FACTOR CORRECTION

PURPOSE.

Capacitors are normally used to improve power factor. Although power factor correction capacitors are not usually applied to military interior electrical systems, their use is discussed here for completeness. Figure 1 shows a typical configuration in which a shunt capacitor is added to improve the power factor.

Figure 1 Capacitor Installation for Power Factor Correction
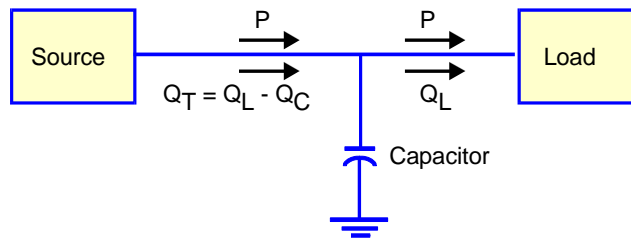
Power factor correction is usually justified for the following reasons:

- To improve voltage.

- To lower the cost of energy, when the electric utility rates vary with the power factor at the metering point.

- To reduce the energy losses in conductors.

- To utilize the full capacity of transformers, switches, overcurrent devices, buses, and conductors for active power predominantly, thereby lowering the capital investment and annual costs.

- To reduce overload of fully loaded motors.

Capacitor installations can have adverse effects on facility operation. The following effects must be considered as part of the overall design:

- Capacitor switching causes surge voltages, which can necessitate the use of surge protection.

- Capacitors can affect the operation of nonlinear loads.

Although capacitors are commonly used for power factor correction, their use requires careful evaluation of the overall facility design. Without a proper design evaluation, capacitors can introduce other problems that offset the potential benefit of a higher power factor.

DETERMINING CAPACITOR SIZE.

Determine the required capacitor size to improve power factor in accordance with the following expression:

$$kVAR_{cap} = kW \times (\tan\theta_1 - \tan\theta_2)$$

where,

$kVAR_{cap}$ = Required capacitor size in kVARs

kW = Active power in circuit

θ_1 = Phase angle before applying power factor correction

θ_2 = Desired phase angle after power factor correction

Figure 2 shows the phasor relationship for power factor correction. The addition of kVARs by a shunt capacitor reduces the supplied kVAR.

Figure 2 Phasor Diagram for Power Factor Correction
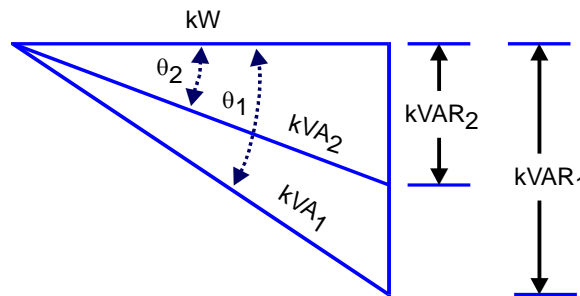
EXAMPLE: A three-phase, 460-volt, 50 horsepower (37,300 watts) motor has a power factor of 0.65. What capacitor rating is needed to improve the power factor to 0.95?

First, calculate the power required by the motor at full-load conditions. NEC Table 430.250 (2005 Edition) specifies a typical full-load current of 65 amperes. The load power is then calculated by:

$$P(kW) = \frac{\sqrt{3} \times V \times I \times pf}{1000} = \frac{1.73 \times 460 \times 65 \times 0.65}{1000} = 33.7\ kW$$

For a power factor of 0.65, cos θ_1 = 0.65, or θ_1 = 49.46°, and tan θ_1 = 1.17. The desired power factor is 0.95, or θ_2 = 18.19°, and tan θ_2 = 0.33. The required capacitor size is given by:

$$kVAR_{cap} = kW \times (\tan\theta_1 - \tan\theta_2) = 33.7 \times (1.17 - 0.33) = 28.3\ kVAR$$

Look-up tables are often used to perform the above calculation. Table 1 shows a typical table.

EXAMPLE: The previous example determined the required capacitor size for an active power of 33.7 kW with a power factor of 0.65 to obtain a desired power factor is 0.95. Using Table 1, the applicable correction factor is 0.84 and the required capacitor size is:

33.7 kW x 0.84 = 28.3 kVAR.

Table 1 Correction Factors for Capacitor Sizing

Original Power Factor	Desired Power Factor							
	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93
0.50	1.139	1.165	1.192	1.220	1.248	1.276	1.303	1.337
0.51	1.093	1.119	1.146	1.174	1.202	1.230	1.257	1.291
0.52	1.051	1.077	1.104	1.132	1.160	1.188	1.215	1.249
0.53	1.007	1.033	1.060	1.088	1.116	1.144	1.171	1.205
0.54	0.966	0.992	1.019	1.047	1.075	1.103	1.130	1.164
0.55	0.926	0.952	0.979	1.007	1.035	1.063	1.090	1.124
0.56	0.887	0.913	0.940	0.968	0.996	1.024	1.051	1.085
0.57	0.849	0.875	0.902	0.930	0.958	0.986	1.013	1.047
0.58	0.812	0.838	0.865	0.893	0.921	0.949	0.976	1.010
0.59	0.775	0.801	0.828	0.856	0.884	0.912	0.939	0.973
0.60	0.741	0.767	0.794	0.822	0.849	0.878	0.905	0.939
0.61	0.706	0.732	0.759	0.787	0.815	0.843	0.870	0.904
0.62	0.672	0.698	0.725	0.753	0.781	0.809	0.836	0.870
0.63	0.640	0.666	0.693	0.721	0.749	0.777	0.804	0.838
0.64	0.607	0.633	0.660	0.688	0.716	0.744	0.771	0.805
0.65	0.576	0.602	0.629	0.657	0.685	0.713	0.740	0.774
0.66	0.545	0.571	0.598	0.626	0.654	0.682	0.709	0.743
0.67	0.515	0.541	0.568	0.596	0.624	0.652	0.679	0.713
0.68	0.486	0.512	0.539	0.567	0.595	0.623	0.650	0.684
0.69	0.456	0.482	0.509	0.537	0.565	0.593	0.620	0.654
0.70	0.427	0.453	0.480	0.508	0.536	0.564	0.591	0.625
0.71	0.399	0.425	0.452	0.480	0.508	0.536	0.563	0.597
0.72	0.370	0.396	0.423	0.451	0.479	0.507	0.534	0.568
0.73	0.343	0.369	0.396	0.424	0.452	0.480	0.507	0.541
0.74	0.316	0.342	0.369	0.397	0.425	0.453	0.480	0.514
0.75	0.289	0.315	0.342	0.370	0.398	0.426	0.453	0.487
0.76	0.262	0.288	0.315	0.343	0.371	0.399	0.426	0.460
0.77	0.236	0.262	0.289	0.317	0.345	0.373	0.400	0.434
0.78	0.210	0.236	0.263	0.291	0.319	0.347	0.374	0.408
0.79	0.183	0.209	0.236	0.264	0.292	0.320	0.347	0.381
0.80	0.157	0.183	0.210	0.238	0.266	0.294	0.321	0.355
0.81	0.131	0.157	0.184	0.212	0.240	0.268	0.295	0.329
0.82	0.105	0.131	0.158	0.186	0.214	0.242	0.269	0.303
0.83	0.079	0.105	0.132	0.160	0.188	0.216	0.243	0.277
0.84	0.053	0.079	0.106	0.134	0.162	0.190	0.217	0.251
0.85	0.027	0.053	0.080	0.108	0.136	0.164	0.191	0.225

Table 1. Correction Factors for Capacitor Sizing, continued

Original Power Factor	Desired Power Factor						
	0.94	0.95	0.96	0.97	0.98	0.99	1.00
0.50	1.369	1.402	1.441	1.481	1.529	1.590	1.732
0.51	1.320	1.357	1.395	1.435	1.483	1.544	1.686
0.52	1.281	1.315	1.353	1.393	1.441	1.502	1.644
0.53	1.237	1.271	1.309	1.349	1.397	1.458	1.600
0.54	1.196	1.230	1.268	1.308	1.356	1.417	1.559
0.55	1.156	1.190	1.228	1.268	1.316	1.377	1.519
0.56	1.117	1.151	1.189	1.229	1.277	1.338	1.480
0.57	1.079	1.113	1.151	1.191	1.239	1.300	1.442
0.58	1.042	1.076	1.114	1.154	1.202	1.263	1.405
0.59	1.005	1.039	1.077	1.117	1.165	1.226	1.368
0.60	0.971	1.005	1.043	1.083	1.131	1.192	1.334
0.61	0.936	0.970	1.008	1.048	1.096	1.157	1.299
0.62	0.902	0.936	0.974	1.014	1.062	1.123	1.265
0.63	0.870	0.904	0.942	0.982	1.030	1.091	1.233
0.64	0.837	0.871	0.909	0.949	0.997	1.058	1.200
0.65	0.806	0.840	0.878	0.918	0.966	1.027	1.169
0.66	0.775	0.809	0.847	0.887	0.935	0.996	1.138
0.67	0.745	0.779	0.817	0.857	0.905	0.966	1.108
0.68	0.716	0.750	0.788	0.828	0.876	0.937	1.079
0.69	0.686	0.720	0.758	0.798	0.840	0.907	1.049
0.70	0.657	0.691	0.729	0.769	0.811	0.878	1.020
0.71	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.72	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.73	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.74	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.75	0.519	0.553	0.591	0.631	0.673	0.740	0.882
0.76	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.77	0.466	0.500	0.538	0.578	0.620	0.687	0.829
0.78	0.440	0.474	0.512	0.552	0.594	0.661	0.803
0.79	0.413	0.447	0.485	0.525	0.567	0.634	0.776
0.80	0.387	0.421	0.459	0.499	0.541	0.608	0.750
0.81	0.361	0.395	0.433	0.473	0.515	0.582	0.724
0.82	0.335	0.369	0.407	0.447	0.489	0.556	0.698
0.83	0.309	0.343	0.381	0.421	0.463	0.530	0.672
0.84	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.85	0.257	0.291	0.329	0.369	0.417	0.478	0.620

CAPACITOR RATINGS.

Capacitors are built to standard sizes as specified by IEEE 18, *IEEE Standard for Shunt Power Capacitors*. Table 2 shows the capacitor sizes of potential interest to facility interior electrical design.

Table 2 Common Capacitor Reactive Power Ratings

Voltage Rating (rms)	kVAR Rating	Number of Phases	BIL kV
216	5, 7.5, 131/3, 20, and 25	1 or 3	30
240	2.5, 5, 7.5,10, 25, 20, 25, and 50	1 or 3	30
480	5, 10, 15, 20 25, 35, 50, 60, and 100	1 or 3	30
600	5, 10, 15, 20 25, 35, 50, 60, and 100	1 or 3	30
2,400	50, 100, 150, and 200	1	75
2,770	50, 100, 150, and 200	1	75
4,160	50, 100, 150, and 200	1	75
7,200	50, 100, 150, 200, 300, and 400	1	95
12,470	50, 100, 150, 200, 300, and 400	1	95
13,800	50, 100, 150, 200, 300, and 400	1	95 and 125

Refer to IEEE 18 for ratings at other voltages.

The calculated capacitor size will rarely exactly match one of the available sizes. The decision of whether to select the next larger or the next smaller size depends on the circuit configuration and the desired power factor.

IEEE 18 establishes the required design tolerances for capacitors.

DESIGN CRITERIA.

Consider requiring power factor correction as part of the facility design. Power factor correction has to be justifiable based upon operational performance improvements or cost-savings, including any potential effects caused by interaction with other devices.

If used, apply capacitors to obtain a power factor range of 0.85 to 0.95. A power factor of 0.85 will satisfy most operational requirements, but the actual minimum value should also be based on any revenue metering penalties established by the local commercial utility for low power factors. Little, if any, economic advantage will usually be realized if attempting to correct above a power factor of 0.95. Ensure that power factor correction will not cause a leading power factor under no-load conditions.

Power factor correction requires particular attention if nonlinear loads are a significant portion of the facility load; this includes electronic equipment, ASDs, UPS systems, and other significant sources of harmonic distortion. Capacitors can resonate with nonlinear loads and cause additional distortion of the electrical system voltage and current. In this case, the capacitor(s) might not improve the power factor at all. Also, resonant conditions can cause capacitor failure. If facilities contain a significant proportion of nonlinear loads, evaluate the application of a synchronous condenser instead. Synchronous condensers are

often applied at the service entrance, which might not solve all power factor problems throughout the facility.

For facility applications, continuously energized capacitors are preferred over switching capacitors, even though this might necessitate the addition of a smaller amount of capacitance. If a pre-selected quantity of capacitors cannot be connected and left connected to the line in a constantly energized state, the facility electrical system would probably be better off without them. Each capacitor on-off cycle causes transient voltage surges that are potentially damaging to other equipment over time. Additional design considerations such as soft-start or pre-insertion resistors are necessary if capacitors are routinely switched. Also, apply surge protection for switched capacitors. Refer to IEEE 141 for additional design considerations for switched capacitors.

Evaluate capacitors installed strictly for motor applications based on the number of motors to have power factor correction. If only a single motor or a small number of motors require power factor correction, the capacitor can be installed at each motor such that it is switched on and off with the motor. If several motors connected to a single bus require power factor correction, install the capacitor(s) at the bus. For new installations, specify the MCC to contain the capacitor(s). For existing installations, determine if spare cubicles can be refurbished to accept the capacitor(s). Refer to NEMA MG 1, IEEE 141 and IEEE 1036, *IEEE Guide for Application of Shunt Power Capacitors*, for additional information.

Do not install capacitors directly onto a motor circuit under the following conditions:

- If solid-state starters are used.

- If open-transition starting is used.

- If the motor is subject to repetitive switching, jogging, inching, or plugging.

- If a multi-speed motor is used.

- If a reversing motor is used.

- If a high-inertia load is connected to the motor.

Size the ampacity of capacitor circuit conductors at least 135 percent of the rated capacitor current in accordance with NEC Article 460.8 (2005 Edition). Provide overcurrent protection and disconnection means as specified by the NEC. IEEE 1036 provides additional guidance for sizing protective devices for the maximum possible inrush current.

Consult with the manufacturer before applying a capacitor under any of the specified abnormal service conditions of IEEE 18.

Liquid dielectrics used in capacitors must be non-PCB mineral oil or other less flammable liquid type. Do not use tetrachloroethylene (perchloroethylene) and 1,2,4, trichlorobenzen fluids.

Provide all capacitors used for power factor correction with an automatic means of draining the stored charge after the capacitor is disconnected from its source of supply.

Power capacitors can fail in such a manner to cause "noise" on communication lines. Ensure that capacitors are not located near communications equipment.

REFERENCE CRITERIA.

The following references provide additional information regarding power factor correction:

- IEEE 18—provides information regarding the ratings and testing of capacitors.

- IEEE 141—provides a detailed technical overview of power factor correction.

- IEEE 519—addresses power factor correction in a nonlinear load environment.

- IEEE 1036—provides application guidelines for shunt power capacitors and is intended for 2,400 volts and higher, although the principles apply to lower voltage applications also.

- NEC Article 460—provides marking, installation, protection, and grounding requirements for capacitors.

- NEMA MG 1—provides recommendations regarding the application of capacitors to motor circuits.