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TechTopics No. 20

Power factor correction capacitor - sizing for motors

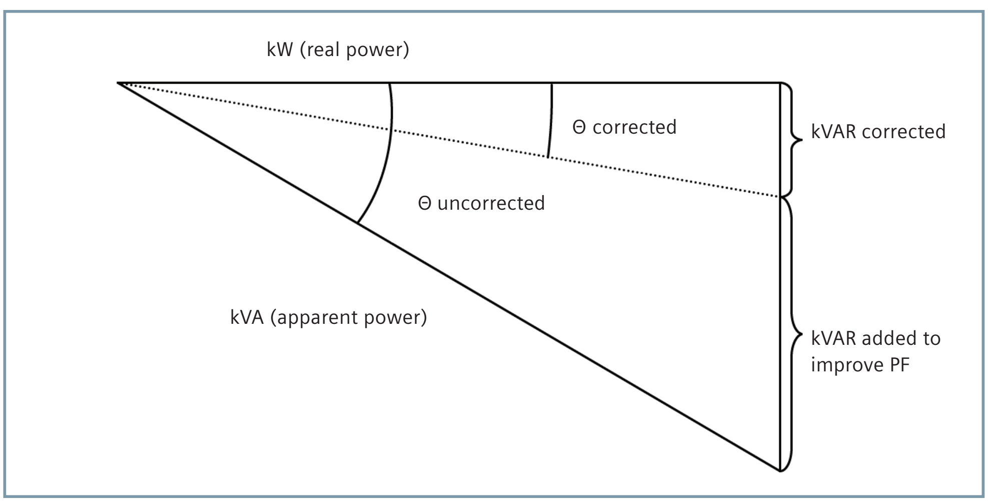
Use of power factor correction has increased significantly in recent years as utilities have implemented power factor penalty clauses in their supply contracts. Apart from the energy cost implications, poor power factor is undesirable because a low power factor requires larger size conductors for a given kW load. Higher line currents associated with a low power factor also result in higher losses in the conductors and in transformers for a given kW load.

Power factor basics

Power factor is the ratio of the real power (kW) to the apparent power (kVA), as shown in the figure below. Mathematically, the power factor is the cosine of the angle Θ.

To understand how to compensate for the poor power factor of a motor, we need to look at the components of the motor current. The real power-producing work is done by the resistive component of the current, which varies with the load on the motor. The reactive current of the motor consists of two components. The first is the magnetizing current that establishes the magnetic flux in the core, which allows the motor to function. The magnetizing current is essentially constant regardless of load.

The second component of reactive current is the leakage reactance current, and this component varies according to the load on the motor.



Answers for infrastructure.

The leakage reactance current is relatively small, so that the total reactive current is relatively constant (compared to the kW variation) over the range of motor no-load to motor full-load. For a range of medium-voltage machines sampled, the ratio between full-load reactive current and no-load reactive current varied from 140 percent to 260 percent (depending on machine design, speed and voltage). For perspective, the ratio between full-load kW and no-load kW is in the order of 4,000 percent.

Because the variation in reactive current is relatively low over the load range of the machine, a capacitor sized to compensate to a desired power factor level at full load will maintain the power factor in the near vicinity of the desired level over the entire load range. Typically, a capacitor sized to correct full-load power factor to 95 percent will maintain power factor in the 95 percent to 98 percent area over the full range from no-load to full-load.

The switching device and the conductors used to connect to the power factor correction capacitors must be sized for at least 135 percent of the rated current of the capacitors, as required by Article 460 of the National Electrical Code® (NFPA 70®) (NEC®).

Location of power factor correction capacitors

Ideally, power factor capacitors should be connected on the load side of the contactor and switched as a unit with the motor. This arrangement minimizes the switching costs, as an additional switching device is not needed. This also provides a path for the capacitor to discharge quickly when the contactor is opened. More importantly, it automatically adds capacitance to the system only when the load with the poor power factor is present. This avoids the possibility of over-compensation in the system, which can occur with large bulk capacitors.

If the capacitors are connected on the load side of the contactor, but on the line side of the current transformers used for the overload relay, the settings of the overload relay can be based directly on the (uncorrected) motor data. If the capacitors are connected on the load (motor) side of the current transformers, the settings for the overload relay must be determined from the motor data, adjusted by the effect of the power factor correction capacitors. To avoid this complication, it is preferred that the capacitors be connected on the line side of the current transformers.

Do not connect power factor capacitors directly to the motor when:

- Using a solid-state (“soft”) starter
- Using open-transition on reduced-voltage starters (high-transient torques)
- If the motor can be restarted before it has a chance to slow down appreciably (high-transient torques)
- If the motor load is a high-inertia load (long deceleration time and self-excitation)
- For reversing machines (high-transient torques)
- For two-speed motors.

Over-correction (and self-excitation)

It is important not to over-correct when sizing capacitors that are connected in parallel with the motor. The motor requires reactive power (kVARs) to create the magnetic flux. The power factor correction capacitor can supply the kVARs required by the motor when the motor is switched off. At the instant that the motor is switched off, the motor and the driven load are at full speed. When the motor is switched off, the motor and load inertia will continue to drive the motor. If the magnetizing current required by the motor is available from the charged capacitor, the motor will operate as a voltage generator and maintain the voltage on the motor.

In the preferred situation, the power factor correction capacitors are sized at or below 90 percent of the no-load kVAR requirement of the motor. If the capacitors are too large, the motor can be subjected to self-excitation, which will result in excessive voltages applied to the capacitors and motor. The capacitors are sized based on 90 percent of the no-load kVAR requirement because the manufacturing tolerance of the capacitors is –0 percent, +15 percent.

The parallel combination of the capacitors and the motor inductance forms a resonant circuit. If the capacitance is lower than the magnetizing reactance of the motor (under-correction), the resonant frequency is higher than the power system frequency. Thus, as the motor slows down after disconnection, the generated voltage will not pass through the resonant frequency, and the voltage to which the motor is exposed will not be hazardous.

On the other hand, if the capacitance is equal to the magnetizing reactance of the motor (critical-correction), the resonant frequency equals the power system frequency. Under this situation, the motor can be exposed to overvoltage due to self-excitation.

Finally, if the capacitance is larger than the magnetizing reactance of the motor (over-corrected), the resonant frequency is less than the frequency of the power system. Thus, as the motor slows down after disconnection, the generated voltage frequency will pass through the resonant frequency of the inductive-capacitive circuit. Tests have shown that the voltage on the motor and capacitors can range up to 175 percent of normal system voltage, and can result in damage to the capacitors, the motor and the driven load.

Because of the hazards of self-excitation, ANSI/IEEE 18-1992 stated that the total kVAR of capacitors connected in parallel with the motor shall not exceed the amount of kVAR required to correct the no-load power factor to unity, in order to avoid overvoltage due to self-excitation. This same requirement was contained in the NEC as recently as 1981, but has (unfortunately) been dropped from later editions.

When the 2002 edition of IEEE 18 was issued, this requirement was transferred to a new application guide for shunt capacitors, IEEE 1036, and in the 2010, this valuable information was deleted. Instead, reference was made to IEEE 141 (the “Red” book), where it appears in clause 8.9.3.2.

Excessive torque on re-energization

Power factor correction capacitors should not be used if the motor can be re-energized quickly after disconnection. When capacitors are connected in parallel with the motor inductance, the capacitor can supply some or all of the current required to create the magnetic flux. As the motor continues to rotate due to the motor and load inertia, the motor generates a voltage. As the motor slows, this voltage moves out-of-phase with the system voltage. In the worst case (with capacitors oversized, high-inertia load and a motor with a steep magnetization curve), the generated voltage can reach 175 percent of system voltage. If re-energization occurs under this condition, with the system voltage and the motor voltage 180° out-of-phase, the motor can be subjected to transient torques far in excess of its capabilities. In tests, transient torques as high as 20 times normal have been measured.

As a general guide, if the kVAR of the capacitors is equal to or less than the motor magnetizing kVAR, and the motor load is not a high-inertia load, the generated voltage should decay within about five seconds. Therefore, the motor should not be re-energized for at least five seconds after disconnection when using parallel-connected power factor correction capacitors.

Sizing of power factor correction capacitors

The preferred size for power factor correction capacitors should (ideally) be provided by the motor manufacturer. If the motor manufacturer's recommendation is not available, the size of the capacitors can be determined as described in this section.

Mathematically, the kVARs required for correction can be computed from the relations shown in the figure on page four, and from the following equations:

$$\text{kVAR} = \text{kW} \times \tan \Theta$$

$$\text{kVAR}_{\text{uncorrected}} = \text{kW} \times \tan \Theta_{\text{uncorrected}}$$

$$\text{kVAR}_{\text{corrected}} = \text{kW} \times \tan \Theta_{\text{corrected}}$$

$$\text{kVAR}_{\text{required for correction}} = \text{kW} \times (\tan \Theta_{\text{uncorrected}} - \tan \Theta_{\text{corrected}})$$

A simplified procedure for determining the size of power factor correction capacitors is:

1. Obtain motor data from the manufacturer:
   - (Preferred) no-load magnetizing kVAR (this may be difficult to obtain)
   - (Second best) motor no-load amperes from motor manufacturer (or, measure no-load amperes with machine running)
   - Motor horsepower (HP), full-load efficiency, full-load power factor (PF).
2. Determine desired corrected PF (not over 95 percent).
3. Calculate required kVARs as:

   $$\text{kVAR}_{\text{required for correction}} = \\ [\text{HP} \times 0.746 \text{ (watts/HP)/efficiency}] \times \text{factor from table}$$

   (The factor shown in the table is the difference in the tangents of the power factor angle for uncorrected and corrected PF.)
4. Calculate no-load (motor magnetizing) kVAR.

   $$\text{kVAR}_{\text{motor magnetizing}} = \\ \text{no-load (A)} \times \text{motor voltage (kV)} \times 1.732$$

   (**Note:** This is not mathematically correct, but the error is less than one percent provided the no-load power factor is less than about 14 percent.)
5. Compare (desired) $\text{kVAR}_{\text{required for correction}}$ to 0.90 x (no-load) $\text{kVAR}_{\text{motor magnetizing}}$. Select capacitors equal to the desired kVAR, but never more than 0.90 x no-load kVAR. If this does not match a standard capacitor size, use the next smaller size.

References:

- ANSI/IEEE 18-1992, "Shunt Power Capacitors," clause 8.3.1
- ANSI/NFPA 70-2011, "National Electrical Code (NEC)," Article 460
- ANSI/NFPA 70-1981, "National Electrical Code (NEC)," Article 460-7(a)
- ANSI/IEEE 141-1993, "Recommended Practice for Electric Power Distribution for Industrial Plants," clause 8.9
- Beeman, D. "Industrial Power Systems Handbook," McGraw-Hill (1955), Chapter 8.

Correction factors for capacitor selection

Uncorrected power factor	Desired corrected power factor															
	85.0	86.0	87.0	88.0	89.0	90.0	90.5	91.0	91.5	92.0	92.5	93.0	93.5	94.0	94.5	95.0
60	0.714	0.740	0.767	0.794	0.821	0.849	0.863	0.878	0.892	0.907	0.923	0.938	0.954	0.970	0.987	1.005
61	0.679	0.706	0.732	0.759	0.787	0.815	0.829	0.843	0.858	0.873	0.888	0.904	0.920	0.936	0.953	0.970
62	0.646	0.672	0.699	0.726	0.753	0.781	0.795	0.810	0.825	0.839	0.855	0.870	0.886	0.903	0.919	0.937
63	0.613	0.639	0.666	0.693	0.720	0.748	0.763	0.777	0.792	0.807	0.822	0.837	0.853	0.870	0.887	0.904
64	0.581	0.607	0.634	0.661	0.688	0.716	0.731	0.745	0.760	0.775	0.790	0.805	0.821	0.838	0.854	0.872
65	0.549	0.576	0.602	0.629	0.657	0.685	0.699	0.714	0.728	0.743	0.758	0.774	0.790	0.806	0.823	0.840
66	0.519	0.545	0.572	0.599	0.626	0.654	0.668	0.683	0.697	0.712	0.728	0.743	0.759	0.775	0.792	0.810
67	0.488	0.515	0.541	0.568	0.596	0.624	0.638	0.652	0.667	0.682	0.697	0.713	0.729	0.745	0.762	0.779
68	0.459	0.485	0.512	0.539	0.566	0.594	0.608	0.623	0.637	0.652	0.667	0.683	0.699	0.715	0.732	0.750
69	0.429	0.456	0.482	0.509	0.537	0.565	0.579	0.593	0.608	0.623	0.638	0.654	0.670	0.686	0.703	0.720
70	0.400	0.427	0.453	0.480	0.508	0.536	0.550	0.565	0.579	0.594	0.609	0.625	0.641	0.657	0.674	0.692
71	0.372	0.398	0.425	0.452	0.480	0.508	0.522	0.536	0.551	0.566	0.581	0.597	0.613	0.629	0.646	0.663
72	0.344	0.370	0.397	0.424	0.452	0.480	0.494	0.508	0.523	0.538	0.553	0.569	0.585	0.601	0.618	0.635
73	0.316	0.343	0.370	0.396	0.424	0.452	0.466	0.481	0.495	0.510	0.525	0.541	0.557	0.573	0.590	0.608
74	0.289	0.316	0.342	0.369	0.397	0.425	0.439	0.453	0.468	0.483	0.498	0.514	0.530	0.546	0.563	0.580
75	0.262	0.289	0.315	0.342	0.370	0.398	0.412	0.426	0.441	0.456	0.471	0.487	0.503	0.519	0.536	0.553
76	0.235	0.262	0.288	0.315	0.343	0.371	0.385	0.400	0.414	0.429	0.444	0.460	0.476	0.492	0.509	0.526
77	0.209	0.235	0.262	0.289	0.316	0.344	0.359	0.373	0.388	0.403	0.418	0.433	0.449	0.466	0.483	0.500
78	0.183	0.209	0.236	0.263	0.290	0.318	0.332	0.347	0.361	0.376	0.392	0.407	0.423	0.439	0.456	0.474
79	0.156	0.183	0.209	0.236	0.264	0.292	0.306	0.320	0.335	0.350	0.365	0.381	0.397	0.413	0.430	0.447
80	0.130	0.157	0.183	0.210	0.238	0.266	0.280	0.294	0.309	0.324	0.339	0.355	0.371	0.387	0.404	0.421
81	0.104	0.131	0.157	0.184	0.212	0.240	0.254	0.268	0.283	0.298	0.313	0.329	0.345	0.361	0.378	0.395
82	0.078	0.105	0.131	0.158	0.186	0.214	0.228	0.242	0.257	0.272	0.287	0.303	0.319	0.335	0.352	0.369
83	0.052	0.079	0.105	0.132	0.160	0.188	0.202	0.216	0.231	0.246	0.261	0.277	0.293	0.309	0.326	0.343
84	0.026	0.053	0.079	0.106	0.134	0.162	0.176	0.190	0.205	0.220	0.235	0.251	0.267	0.283	0.300	0.317
85	0.000	0.026	0.053	0.080	0.107	0.135	0.150	0.164	0.179	0.194	0.209	0.225	0.240	0.257	0.274	0.291
86		0.000	0.027	0.054	0.081	0.109	0.123	0.138	0.152	0.167	0.183	0.198	0.214	0.230	0.247	0.265
87			0.000	0.027	0.054	0.082	0.097	0.111	0.126	0.141	0.156	0.172	0.187	0.204	0.221	0.238
88				0.000	0.027	0.055	0.070	0.084	0.099	0.114	0.129	0.145	0.160	0.177	0.194	0.211
89					0.000	0.028	0.042	0.057	0.071	0.086	0.102	0.117	0.133	0.149	0.166	0.184
90						0.000	0.014	0.029	0.043	0.058	0.074	0.089	0.105	0.121	0.138	0.156
91								0.000	0.015	0.030	0.045	0.060	0.076	0.093	0.110	0.127
92										0.000	0.015	0.031	0.047	0.063	0.080	0.097
93												0.000	0.016	0.032	0.049	0.067
94														0.000	0.017	0.034
95																0.000

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