Subject: POWER FACTOR CORRECTION CAPACITOR—APPLICATIONS

INTRODUCTION

The vast majority of the total load connected to today's industrial power systems is inductive and has a low operating power factor. In most installations, low power factor is caused by oversized or lightly loaded induction motors. Other causes of low power factor include: fluorescent and HID lighting, battery chargers, arc welders, induction furnaces, rectifiers, and other electronic equipment.

A low operating power factor usually results in poor electrical efficiency, wastes money in the form of increased power bills and places an extraneous burden on the entire power system.

Properly selected and installed, power factor correction capacitors provide an economical means for improving a systems power factor. Benefits stemming from the addition of capacitors to a power system include reduced power cost, a release of system capacity, reduced power losses and improved voltage levels.

POWER FACTOR FUNDAMENTALS

The total current required by inductive loads such as motors, transformers, and fluorescent lighting may be considered to be made up of two separate types of current.

Active current (or power producing current) is the current which is converted into useful work such as turning a lathe, providing light or pumping water. The power produced by this component is the *kilowatt* (kW).

Reactive current (also known as wattless, magnetizing or nonworking current) is the current which provides the flux necessary for the operation of these loads but is not converted into useful work. The power produced by this component is the *kilovar* (kvar).

The *total current* is the current which is measured on an ammeter. It is the sum of both the active and the reactive components. The power produced by the total current is measured in *kilovolt amperes* (kVA).

Power Triangle

The relations between the various power components and the system voltage are illustrated in the power triangle shown in Figure 1. From Figure 1, it is apparent that the active power component is *in phase* with the applied voltage while the reactive component occurs 90 degrees out of phase with the voltage.

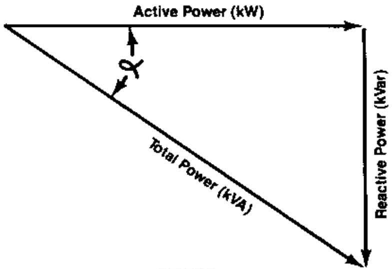


FIGURE 1

When calculating the arithmetic sum of the two components, the simple rule of addition (e.g. 2 + 2 = 4) cannot be used. Instead, the total power must be determined from the right hand triangle relation as follows:

$$(\text{total power})^2 = (\text{active power})^2 + (\text{reactive power})^2$$

POWER FACTOR

Power factor, as defined in this discussion, is the ratio of the active power component to the total power. This ratio can vary between zero and one and is often expressed as a percent.

$$\text{power factor} = \frac{\text{active power}}{\text{total power}} = \text{cosine}\ (\propto)$$

Example: Determine the power factor of a 500 kW, 460V. three phase load which draws 750A.

The total power in a three phase circuit equals:

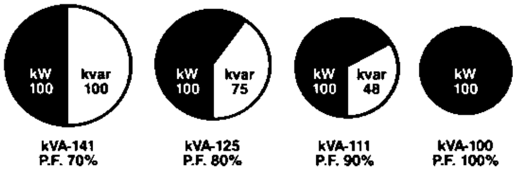
$$\text{kVA} = \frac{\sqrt{3} \times \text{volts} \times \text{amperes}}{1000} = \frac{1.73 \times 460 \times 750}{1000} = 596.8$$

Power factor = kW/kVA or 500/596.8 = 0.838, or 83.8%.

High and Low Power Factor

When the active power component equals the total power, such as for a purely resistive load, the power factor of the load will be 1/1 or *unity*. This is referred to as a *high* power factor. However, most loads require both active and reactive power components and the power factor will depend on the loads reactance/resistance (X/R) ratio. If the loads reactance is large in comparison with its resistance, then the power factor is referred to as being *low*.

The effects of a low operating power factor are illustrated in Figure 2.



Decreasing size of conductors required to carry the same 100kW (working power) at power factors ranging from 70% to 100%.

FIGURE 2

Leading and Lagging Power Factor

The power factor angle (∝) in Figure 1 represents a time shift which occurs between voltage and current when the load contains a reactive element. The degree of this *phase shift* is dependent upon the loads reactance. In a purely resistive load, voltage and current peaks will occur simultaneously as shown in Figure 3 for the voltage (V.) and current (I_R). In this case, the power factor angle (∝) is zero and the power factor (cosine (∝)) is unity. On the other hand, a 90 degree phase shift will occur between voltage and current in a purely reactive load and the power factor will be zero. This is shown in Figure 3 for the current (I_L).

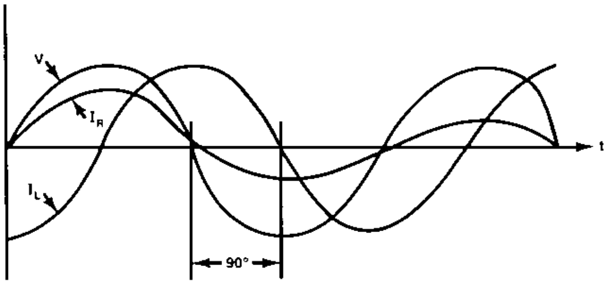


FIGURE 3

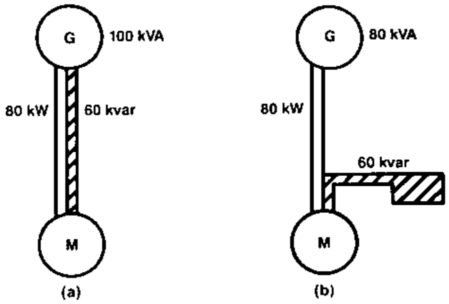
The phase relation of current with respect to voltage will determine if the power factor is leading or lagging. In an inductive load, the current will reach its peak after the voltage peak and the power factor is referred to as *lagging* the voltage. This is shown in Figure 3. On the other hand, a capacitive load will have a *leading* power factor since the current reaches its peak before the voltage.

In the power triangle, a lagging power factor is generally represented with the reactive component pointing in a downward direction as shown in Figure 1 and leading power factors with the reactive component shown in an upward direction.

Power Factor Correction

Power factor can be improved by either increasing the active power component or reducing the reactive component. Of course, increasing the active power component for the sole purpose of power factor correction would not be economically feasible. Thus, the only practical means for improving a systems power factor is to reduce the reactive power component.

One method for reducing this component is to provide it locally at the load. This method will improve the power factor from the point where the reactive power source is connected back to the source. As an example, consider the load in Figure 4a. The total power required is 100 kVA of which 80 kW is active power and 60 kvar is reactive power. If the reactive power is furnished locally (Figure 4b), the power system only has to carry 80 kVA (80 kW). Thus, the power factor (from the point where the reactive power is locally supplied back to the source) is improved to unity.



(a) (b)

FIGURE 4

Capacitors for Power Factor Correction

Properly selected, capacitors offer an ideal means for improving the power factor of an inductive load. When a capacitor is connected to an inductive load, it acts as a reactive power generator locally furnishing the necessary reactive current required by the inductive load. In fact, power factor capacitors are rated in *kvar* to indicate their reactive power generating capability.

Capacitors are able to perform this function since they draw a leading current which will effectively cancel lagging inductive current. If the leading capacitor current equals the inductive lagging current, complete cancellation of the two current components occur and the reactive power component will be reduced to zero. This is illustrated in Figure 5.

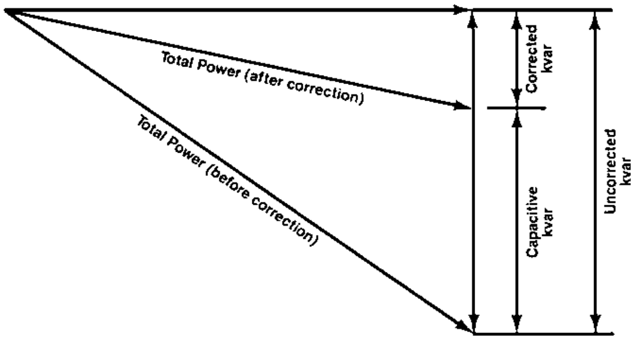


FIGURE 5

Selecting Capacitor kvar Ratings

A convenient method for determining the required capacitive kvar rating to improve the power factor of an inductive load or an entire power system can easily be determined from Table 1, if the power factor and active power component are known.

Example: Determine the capacitive kvar required to improve the power factor of a load from 0.80 lagging to unity if the active power component is 80 kW.

kvar = active power × (kW multiplier from Table 1)
= 80 × (0.75) =60

TABLE 1

DESIRED POWER FACTOR

ORIGINAL POWER FACTOR

	.80	.81	.82	.83	.84	.85	.86	.87	.88	.89	.90	.91	.92	.93	.94	.95	.96	.97	.98	.99	1.0
.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	1.440	1.481	1.529	1.589	1.732
.51	0.937	0.962	0.989	1.015	1.041	1.067	1.094	1.120	1.147	1.175	1.203	1.231	1.261	1.292	1.324	1.358	1.395	1.436	1.484	1.544	1.687
.52	0.893	0.919	0.945	0.971	0.997	1.023	1.050	1.076	1.103	1.131	1.159	1.187	1.217	1.248	1.280	1.314	1.351	1.392	1.440	1.500	1.643
.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	1.308	1.349	1.397	1.457	1.600
.54	0.809	0.835	0.861	0.887	0.913	0.939	0.966	0.992	1.019	1.047	1.075	1.103	1.133	1.164	1.196	1.230	1.267	1.308	1.356	1.416	1.559
.55	0.769	0.795	0.821	0.847	0.873	0.899	0.926	0.952	0.979	1.007	1.035	1.063	1.093	1.124	1.156	1.190	1.227	1.268	1.316	1.376	1.519
.56	0.730	0.756	0.782	0.808	0.834	0.860	0.887	0.913	0.940	0.968	0.996	1.024	1.054	1.085	1.117	1.151	1.188	1.229	1.277	1.337	1.480
.57	0.692	0.718	0.744	0.770	0.796	0.822	0.849	0.875	0.902	0.930	0.958	0.986	1.016	1.047	1.079	1.113	1.150	1.191	1.239	1.299	1.442
.58	0.655	0.681	0.707	0.733	0.759	0.785	0.812	0.838	0.865	0.893	0.921	0.949	0.979	1.010	1.042	1.076	1.113	1.154	1.202	1.262	1.405
.59	0.619	0.645	0.671	0.697	0.723	0.749	0.776	0.802	0.829	0.857	0.885	0.913	0.943	0.974	1.006	1.040	1.077	1.118	1.166	1.226	1.369
.60	0.583	0.609	0.635	0.661	0.687	0.713	0.740	0.766	0.793	0.821	0.849	0.877	0.907	0.938	0.970	1.004	1.041	1.082	1.130	1.190	1.333
.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	1.007	1.048	1.096	1.156	1.299
.62	0.516	0.542	0.568	0.594	0.620	0.646	0.673	0.699	0.725	0.754	0.782	0.810	0.840	0.871	0.903	0.937	0.974	1.015	1.063	1.123	1.266
.63	0.483	0.509	0.535	0.561	0.587	0.613	0.640	0.666	0.693	0.721	0.749	0.777	0.807	0.838	0.870	0.904	0.941	0.982	1.030	1.090	1.233
.64	0.451	0.474	0.503	0.529	0.555	0.581	0.608	0.634	0.661	0.689	0.717	0.745	0.775	0.806	0.838	0.872	0.909	0.950	0.998	1.068	1.201
.65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.713	0.743	0.774	0.806	0.840	0.877	0.918	0.966	1.026	1.169
.66	0.388	0.414	0.440	0.466	0.492	0.518	0.545	0.571	0.598	0.626	0.654	0.682	0.712	0.743	0.775	0.809	0.846	0.887	0.935	0.995	1.138
.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	0.816	0.857	0.905	0.965	1.108
.68	0.328	0.354	0.380	0.406	0.432	0.458	0.485	0.511	0.538	0.566	0.594	0.622	0.652	0.683	0.715	0.749	0.785	0.827	0.875	0.935	1.078
.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	0.757	0.798	0.846	0.906	1.049
.70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.564	0.594	0.625	0.657	0.691	0.728	0.769	0.817	0.877	1.020
.71	0.242	0.268	0.294	0.320	0.346	0.372	0.399	0.425	0.452	0.480	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
.72	0.214	0.240	0.266	0.292	0.318	0.344	0.371	0.397	0.424	0.452	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
.73	0.186	0.212	0.238	0.264	0.290	0.316	0.343	0.369	0.396	0.424	0.452	0.480	0.510	0.541	0.573	0.607	0.644	0.685	0.733	0.793	0.936
.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	0.617	0.658	0.706	0.766	0.909
.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	0.590	0.631	0.679	0.739	0.882
.76	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.288	0.315	0.343	0.371	0.399	0.429	0.460	0.492	0.526	0.563	0.604	0.652	0.712	0.855
.77	0.079	0.105	0.131	0.157	0.183	0.209	0.236	0.262	0.289	0.317	0.345	0.373	0.403	0.434	0.466	0.500	0.537	0.578	0.626	0.686	0.829
.78	0.052	0.078	0.104	0.130	0.156	0.182	0.209	0.235	0.262	0.290	0.318	0.346	0.376	0.407	0.439	0.473	0.510	0.551	0.599	0.659	0.802
.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	0.484	0.525	0.573	0.633	0.776
.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	0.458	0.499	0.547	0.609	0.750
.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	0.432	0.473	0.521	0.581	0.724
.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	0.406	0.447	0.495	0.555	0.698
.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	0.380	0.421	0.469	0.529	0.672
.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	0.354	0.395	0.443	0.503	0.646
.85						0.000	0.027	0.053	0.080	0.108	0.136	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
.86							0.000	0.026	0.053	0.081	0.109	0.137	0.167	0.198	0.230	0.264	0.301	0.342	0.390	0.450	0.593
.87								0.000	0.027	0.055	0.083	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
.88									0.000	0.028	0.056	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
.89										0.000	0.028	0.056	0.086	0.117	0.149	0.183	0.220	0.261	0.309	0.369	0.512
.90											0.000	0.028	0.058	0.089	0.121	0.155	0.192	0.233	0.281	0.341	0.484
.91												0.000	0.030	0.061	0.093	0.127	0.164	0.205	0.253	0.313	0.456
.92													0.000	0.031	0.063	0.097	0.134	0.175	0.223	0.283	0.426
.93														0.000	0.032	0.066	0.103	0.144	0.192	0.252	0.395
.94															0.000	0.034	0.071	0.112	0.160	0.220	0.363
.95																0.000	0.037	0.079	0.126	0.186	0.329
.96																	0.000	0.041	0.089	0.149	0.292
.97																		0.000	0.048	0.108	0.251
.98																			0.000	0.060	0.203
.99																				0.000	0.143
																					0.000

Benefits of Improved Power Factor

An improvement in power factor can provide both economic and system advantages. Direct economic advantages are attained when monetary incentives such as a power factor penalty are enforced. Operational benefits such as improved system efficiency, release of system capacity, reduction of power losses and voltage improvement may also be obtained.

Reduced Power Cost

Electric utilities are obligated to provide the necessary power to their customers. This includes both the customers' active and reactive power requirements. However, the reactive power component does **not** register on the utilities revenue metering. This means the utility must spend extra money in generation and transmission equipment to provide a power component for which there is no direct return.

Consequently, many utilities now include a power factor adjustment clause in their rate structures to compensate for providing this component. These clauses, or *penalties*, provide a strong economic incentive for improving the power factor and often account for a significant portion of the total power bill.

By locally furnishing reactive kvar, the consumer can often enjoy substantial savings by avoiding these penalties.

Example:
Determine required kvar, savings and payback period for an industrial plant subjected to the following conditions:

Demand Charge: $5.00/kW Billing Demand

$$\text{Billing Demand: Actual Demand} \times \frac{0.95}{\text{actual power factor}}$$

Monthly power bills should be first tabulated showing the monthly demand, power factor, billing demand and demand charge for the actual and desired power factor. A twelve month period is normally evaluated to account for both winter and summer demand peaks.

Actual Power Factor

Month	Actual Demand	Power Factor	Billing Demand	Demand Charge
Jan.	227	0.6350	340	$1,698.00
Feb.	257	0.6508	375	1,876.00
Mar.	226	0.6628	324	1,620.00
Apr.	240	0.6780	336	1,681.00
May	219	0.6733	309	1,545.00
June	219	0.6729	309	1,546.00
July	235	0.6339	352	1,761.00
Aug.	251	0.5837	409	2,043.00
Sept.	239	0.5485	414	2,070.00
Oct.	252	0.5502	435	2,176.00
Nov.	238	0.5716	396	1,978.00
Dec.	249	0.5758	411	2,054.00
		Annual Demand Charge		$22,048.00

The tabulation is again performed using a desired power factor of 0.95 as a minimum power factor required to eliminate the penalty.

Desired Power Factor

Month	Actual Demand	Power Factor	Billing Demand	Demand Charge
Jan.	227	0.95	227	$1,135.00
Feb.	257	0.95	257	1,285.00
Mar.	226	0.95	226	1,130.00
Apr.	240	0.95	240	1,200.00
May	219	0.95	219	1,095.00
June	219	0.95	219	1,095.00
July	235	0.95	235	1,175.00
Aug.	251	0.95	251	1,255.00
Sept.	239	0.95	239	1,195.00
Oct.	252	0.95	252	1,260.00
Nov.	238	0.95	238	1,190.00
Dec.	249	0.95	249	1,245.00
		Annual Demand Charge		$14,260.00

Thus, by improving the monthly power factor to 95%, a savings of $7,788. will occur. An additional reduction in the power bill will also result since I^2R is also reduced.

The required capacitive kvar to improve the power factor to 95% is determined for each month by using monthly demand, power factor and Table 1. The results of these calculations are summarized as follows:

Month	Actual Demand	Power Factor Actual	Power Factor Desired	Required kvar
Jan.	227	0.6350	0.95	201.5
Feb.	257	0.6508	0.95	215.4
Mar.	226	0.6628	0.95	181.0
Apr.	240	0.6780	0.95	181.3
May	219	0.6733	0.95	168.5
June	219	0.6729	0.95	168.8
July	235	0.6339	0.95	209.5
Aug.	251	0.5837	0.95	266.7
Sept.	239	0.5485	0.95	285.8
Oct.	252	0.5502	0.95	299.6
Nov.	238	0.5716	0.95	263.4
Dec.	249	0.5758	0.95	271.7

From the above tabulation, at least 299.6 kvar (300 kvar being the nearest available capacitor rating) is required to achieve a 95% power factor for the entire year.

The cost for providing this equipment will depend on the method of correction selected, equipment and labor cost. For this example, a value of $50.00/kvar is selected.

The time required for the power factor improvement project to pay for itself is:

$$\text{payback period} = \frac{\$\text{ cost}}{\$\text{ savings/YR}}$$

$$\text{payback period} = \frac{(300 \times \$50.)}{(\$22{,}048 - \$14{,}260.)}$$

$$= 1.93 \text{ years}$$

Release of System Capacity

When power factor capacitors are located at the terminals of an inductive load, they will deliver all or most of the reactive power required by the load. This means a reduction in system current will occur, permitting additional load to be connected to the system without increasing the size of transformers, switchboards and other distribution equipment.

Often, this release in system capacity is reason enough to warrant an improvement in power factor. Especially when conductors or panels are overheating or where overcurrent devices frequently open.

The percent released capacity resulting from an improvement in power factor is:

$$\%\text{ Released System Capacity} = 100 \times \left(1 - \frac{pf_o}{pf}\right)$$

where: pf_o = original power factor
pf = final power factor after correction

Example:
Determine the system capacity released by improving the power factor from 0.6 to 0.90.

$$\%\text{ Released System Capacity} = 100 \times \left(1 - \frac{.6}{.9}\right)$$

$$= 33.3\%$$

This means that after adding capacitors which correct the system to a .90 power factor, the kVA load or line current is reduced by 33.3% of what it was before pf correction. Putting this another way, with the required capacitors on line, an additional 33.3% kVA load or line current can be added to this system without exceeding the amount utilized before pf correction.

Reduced Power Losses

Another benefit resulting from a power factor improvement project is the reduction in power system losses. This is especially true for older power systems where the kilowatt (I^2R) losses can account for as much as 2-5 percent of the total load.

Since power losses are proportional to the current squared, and the current is proportional to the power factor, an improvement in power factor will cause a reduction in system losses and reduce power bills.

This reduction can be approximated as:

$$\%\text{ loss reduction} = 100 \times 1 - \frac{\text{original power factor}^2}{\text{desired power factor}^2}$$

Voltage Improvement

When capacitors are added to the power system, the voltage level will increase. The percent voltage rise associated with an improvement in power factor can be approximated as:

$$\%\text{ voltage rise} \approx \frac{\text{capacitor kvar} \times \text{transformer \%IZ}}{\text{transformer kVA}}$$

Under normal operating conditions, the percent voltage rise will only amount to a few percent. Therefore, voltage improvement should not be regarded as a primary consideration for a power factor improvement project.

Location of Capacitors

Group Installations

A group installation as shown in Figure 6 consists of a single large capacitor or group of fixed capacitors located at a central point such as a service entrance, bus tap or panelboard.

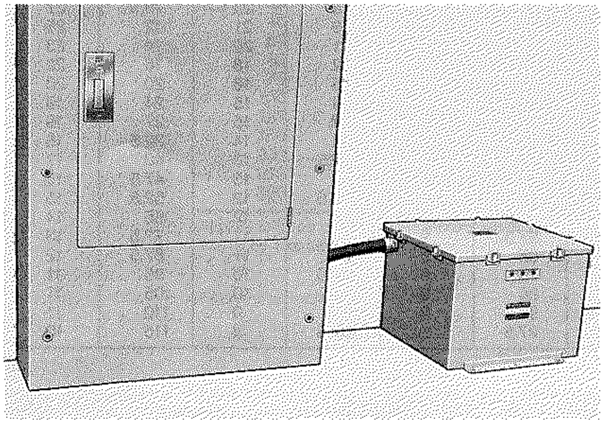


FIGURE 6

The primary advantages of a group installation are installed cost and centralized location. Large capacitors are generally less expensive than smaller capacitors and installation costs are usually lower than installing several capacitors at every low power factor load. Further, if total power requirements remain fairly constant, the group installation can usually respond to a wide diversification of individual loads, thus reducing the total amount of required capacitive kvar.

The primary disadvantage with this type of installation is that it cannot respond to a wide load variation in system load without the possibility of overcorrection during periods of light system loading or undercorrection during heavy load periods. Therefore, the group installation is normally used only when the total connected kvar load is fairly constant.

Automatic Switching

Automatically switched capacitor banks are applied similar to group installations, but are designed to respond to variations in system loading and power factor. These units (Figure 7) contain a programmable microprocessor that continuously monitors system voltage and current (an external CT is required); computes power factor, and initiates switching of internal capacitor banks in or out of service with respect to PF setting. A digital display of PF, kW or kVAR current, and number of energized steps is provided. System power factor is maintained at a programmed level regardless of variations in system loading and with a minimum amount of total purchased kVAR.

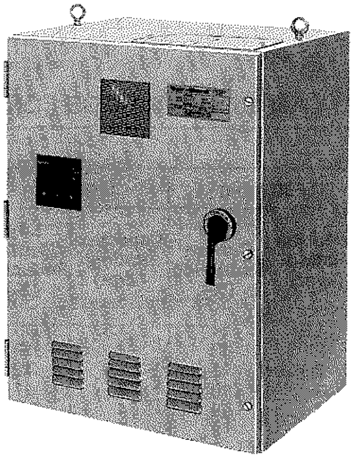


FIGURE 7

Motor Power Factor Correction

Induction or "squirrel-cage" motors constitute the single largest group of low power factor loads connected to most power systems making them prime candidates for power factor correction. Fortunately, their reactive power characteristics are nearly constant throughout the entire operating range (Figure 8) making them ideally suited for the application of capacitors.

Depending on design, the full load power factor of an induction motor can vary anywhere between 80 to 100 percent, but drops rapidly as the load is decreased (Figure 8). However, when a properly selected capacitor is connected to the motor, the operating power factor of the motor-capacitor combination will remain nearly constant over the entire load range (Figure 8).

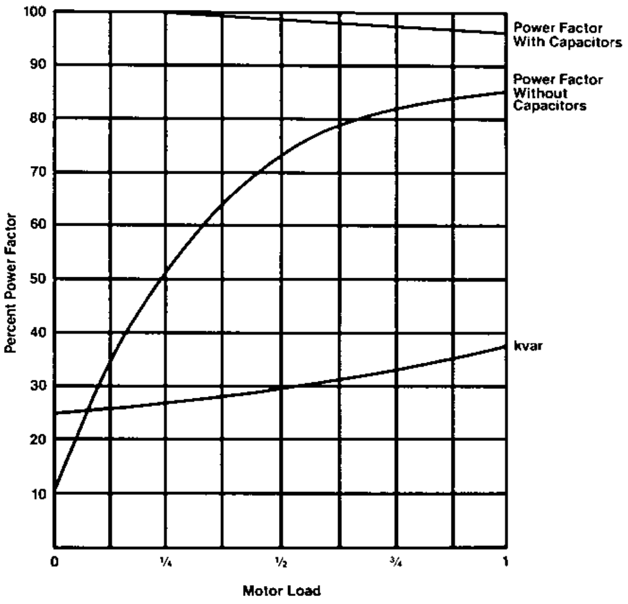


FIGURE 8

Since the capacitor is located at the load, maximum operational benefits are obtained. Overcorrection is also avoided since the capacitor is usually switched on-and-off with the load (Figure 9a, b).

The chief disadvantage of the motor-capacitor installation is the cost. Since capacitors are selected for individual loads they are usually smaller than larger group installations which have a lower cost per kvar. Load diversity is another economic factor which should be considered. If the load is seldom energized, an attractive rate of return on investment may not be realized.

Motor Capacitor Selection

Capacitors must be carefully sized when switched with the motor as a unit, as dangerous overvoltages and transient torques may occur if the capacitor kvar exceeds the motor magnetizing current. Tables 2, 3, and 4 are provided below for proper selection. However, all conditions of these tables must be met to assure overcorrection does not occur. If any condition is in doubt, then the motor manufacturer should be consulted as to the proper amount of capacitance to use.

TABLE 2

SUGGESTED CAPACITOR RATINGS FOR PRE-U-FRAME NEMA CLASS 2B OPEN SQUIRREL - CAGE MOTORS

Induction Motor Rating (hp)	Nominal Motor Speed											
	3600 r/min		1800 r/min		1200 r/min		900 r/min		720 r/min		600 r/min	
	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)
3	1.5	14	1.5	15	1.5	20	2	27	2.5	35	3.5	41
5	2	12	2	13	2	17	3	25	4	32	4.5	37
7½	2.5	11	2.5	12	3	15	4	22	5.5	30	6	34
10	3	10	3	11	3.5	14	5	21	6.5	27	7.5	31
15	4	9	4	10	5	13	6.5	18	8	23	9.5	27
20	5	9	5	10	6.5	12	7.5	16	9	21	12	25
25	6	9	6	10	7.5	11	9	15	11	20	14	23
30	7	8	7	9	9	11	10	14	12	18	16	22
40	9	8	9	9	11	10	12	13	15	16	20	20
50	12	8	11	9	13	10	15	12	19	15	24	19
60	14	8	14	8	15	10	18	11	22	15	27	19
75	17	8	16	8	18	10	21	10	26	14	32.5	18
100	22	8	21	8	25	9	27	10	32.5	13	40	17
125	27	8	26	8	30	9	32.5	10	40	13	47.5	16
150	32.5	8	30	8	35	9	37.5	10	47.5	12	52.5	15
200	40	8	37.5	8	42.5	9	47.5	10	60	12	65	14
250	50	8	45	7	52.5	8	57.5	9	70	11	77.5	13
300	57.5	8	52.5	7	60	8	65	9	80	11	87.5	12
350	65	8	60	7	67.5	8	75	9	87.5	10	95	11
400	70	8	65	6	75	8	85	9	95	10	105	11
450	75	8	67.5	6	80	8	92.5	9	100	9	110	11
500	77.5	8	72.5	6	82.5	8	97.5	9	107.5	9	115	10

Applies to three-phase, 60 Hz motors when switched with capacitors as a single unit.
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TABLE 3
SUGGESTED CAPACITOR RATINGS FOR T-FRAME NEMA CLASS B MOTORS

Induction Motor Rating (hp)	Nominal Motor Speed											
	3600 r/min		1800 r/min		1200 r/min		900 r/min		720 r/min		600 r/min	
	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)	Capacitor Rating (kvar)	Line Current Reduction (%)
3	1.5	14	1.5	23	2.5	28	3	38	3	40	4	40
5	2	14	2.5	22	3	26	4	31	4	40	5	40
7½	2.5	14	3	20	4	21	5	28	5	38	6	45
10	4	14	4	18	5	21	6	27	7.5	36	8	38
15	5	12	5	18	6	20	7.5	24	8	32	10	34
20	6	12	6	17	7.5	19	9	23	10	29	12	30
25	7.5	12	7.5	17	8	19	10	23	12	25	18	30
30	8	11	8	16	10	19	14	22	15	24	22.5	30
40	12	12	13	15	16	19	18	21	22.5	24	25	30
50	15	12	18	15	20	19	22.5	21	24	24	30	30
60	18	12	21	14	22.5	17	26	20	30	22	35	28
75	20	12	23	14	25	15	28	17	33	14	40	19
100	22.5	11	30	14	30	12	35	16	40	15	45	17
125	25	10	36	12	35	12	42	14	45	15	50	17
150	30	10	42	12	40	12	52.5	14	52.5	14	60	17
200	35	10	50	11	50	10	65	13	68	13	90	17
250	40	11	60	10	62.5	10	82	13	87.5	13	100	17
300	45	11	68	10	75	12	100	14	100	13	120	17
350	50	12	75	8	90	12	120	13	120	13	135	15
400	75	10	80	8	100	12	130	13	140	13	150	15
450	80	8	90	8	120	10	140	12	160	14	160	15
500	100	8	120	9	150	12	160	12	180	13	180	15

Applies to three phase, 60 Hz motors when switched with capacitors as a single unit.
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TABLE 4
SUGGESTED CAPACITOR RATINGS IN KILOVAR FOR NEMA CLASS C, D, AND WOUND-ROTOR MOTORS

Induction Motor Rating (hp)	Design C Motor		Design D Motor	
	1800 and 1200 r/min	900 r/min	1200 r/min	Wound-Rotor Motor
15	5	5	5	5.5
20	5	6	6	7
25	6	6	6	7
30	7.5	9	10	11
40	10	12	12	13
50	12	15	15	17.5
60	17.5	18	18	20
75	19	22.5	22.5	25
100	27	27	30	33
125	35	37.5	37.5	40
150	37.5	45	45	50
200	45	60	60	65
250	54	70	70	75
300	65	90	75	85

Applies to three phase, 60 Hz motors when switched with capacitors as a single unit.
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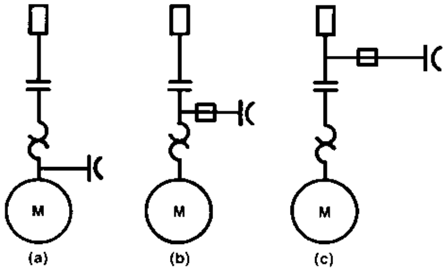
Motors subjected to unusual switching services such as plugging, inching, reversals, multi-speed operation or rapid reclosures should not have capacitors located on the load side of the motor contactor. Instead, the capacitor should be located ahead of the motor starter and switched separately (Figure 9c).



Typical Motor Capacitor Installations

FIGURE 9

Hybrid Installations

Selecting the proper method for applying capacitors is dependent on both the desire for a quick rate of return and maximum operating efficiency. In general, favorable results are achieved by placing fixed and/or automatic banks on feeders and individual capacitors on large motor loads. As an example, consider the electrical system depicted in Figure 10. The lighting loads (10a) operate continuously, therefore a fixed bank of capacitors is used. Capacitors for the large motors (10b) are corrected individually and switched with the load. Smaller motors (10c) are corrected as a group at a panelboard or motor control center with an automatically switched capacitor bank.

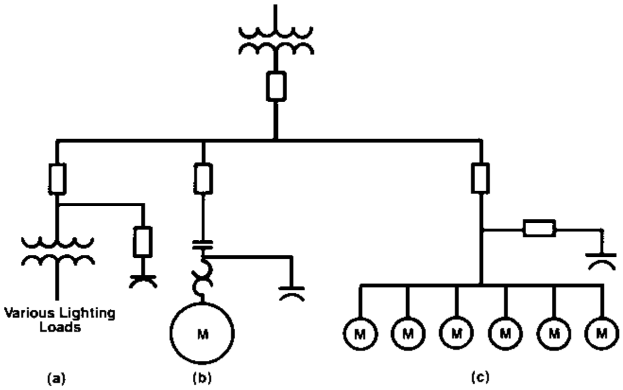


FIGURE 10

Operation of Capacitors

The successful operation of any capacitor is dependent upon its installation and operating environment. Overstressing, overheating, or repeated temperature change will affect the life of any capacitor.

Temperature

Capacitors, unlike most other power apparatus, operate continuously at full load making them more prone to overheating than other equipment. Therefore, it is essential that consideration be given to the proper location to provide for adequate ventilation and dissipation of heat.

In general, capacitors should never be operated in areas where the ambient temperature will exceed 46°C (+115°F) or where the case temperature of the capacitor will exceed 55°C (+131°F).

Voltage

Capacitors cause a rise in the voltage at the point where they are installed and are more prone to overvoltage than other equipment. Further, for economic reasons, capacitors are designed to operate at high voltage stress.

For these reasons, NEMA and ANSI standards require that the shunt capacitors be rated to operate at 110% rated voltage, provided that the crest voltage including all harmonics, does not exceed $1.1 \times \sqrt{2}$ times the rated voltage and provided that the maximum permissible 135% rated kvar is not exceeded. Operation above these limits may shorten the life of the capacitor.

Group installations are especially prone to damage from overvoltage and should be inspected on a regular basis during periods of light system loading when maximum overvoltage will be obtained. If the voltage exceeds the overvoltage limits mentioned above, then the capacitor should either be removed from the line during these high voltage periods, the voltage across the capacitors be reduced, or the capacitors replaced with units having a higher voltage rating. True rms meters are preferred when observing the voltage as they will measure the effects of any harmonics which may be present.

Overvoltages may also occur in motor-capacitor installations if the capacitor current exceeds the motor magnetizing current. Under this condition, the motor may become self-excited when the motor-capacitor is removed from the line. This condition can lead to premature capacitor failure and can also cause transient torques. Careful selection of capacitor ratings will minimize this type of overvoltage from occurring.

Harmonics

The resonant circuit formed by power factor capacitance coupled with source transformer inductance can amplify harmonic currents and voltages present in an electrical system if the harmonic is at or near the circuit resonant frequency. Premature failure of equipment, including capacitors, can result if their design values are exceeded by harmonic/resonant circuit conditions. Although this is a subject of concern growing in proportion to the increasing use of harmonic generating equipment and customer incentives to install power factor capacitors, actual documented occurrences of such problems are few in comparison to all capacitor installations. Capacitors, by design, can tolerate peak voltages of 110%, peak currents of 180%, and maximum operating kVAR of 135% of rated values.

Solutions to known harmonic problems related to capacitor applications can include relatively simple changes in capacitor voltage rating, kVAR sizes or locations (to alter circuit resonant frequency response) to more complex system analysis and application of select harmonic filters. Since it is difficult to predict a damaging combination of system harmonics with applied capacitors, and because only a minority of known capacitor installations have been suspect, a try and see method of applying capacitors is a popular choice. If damaging harmonic levels are known to exist, or the cost of equipment or process at risk is great enough, then a system analysis in advance of the capacitor application may be justified. Consult Square D for further information on this subject.

Installation Guidelines

Conductors

Article 460-8a of the National Electrical Code (NEC) states:

> The ampacity of capacitor circuit conductors shall not be less than 135 percent of the rated current of the capacitor. The ampacity of conductors that connect a capacitor to the terminals of a motor or to motor circuit conductors shall not be less than one third the ampacity of the motor circuit conductors and in no case less than 135% percent of the rated current of the capacitor.

The conductor ratings listed in Tables 5, 6 and 7 are based on 135% rated current and apply for 75°C rated conductors.

TABLE 5

SUGGESTED WIRE, FUSE, SWITCH, AND MOLDED CASE CIRCUIT BREAKER SIZES FOR USE WITH CAPACITORS

240 Volt 3∅/60 Hertz

kvar Rating		Rated Current		Wire Size▲ 75°C Cu		Fuse● Amperes		Fusible Switch Amperes★		Molded Case Circuit Breaker Amperes■	
240V.	208V.	240V.	208V.	240V.	208V.	240V.	208V.	240V.	208V.	240V.	208V.
2.5	1.88	6.0	5.2	14	14	10	10	30	30	15	15
5	3.75	12.0	10.4	12	14	20	20	30	30	20	15
7.5	5.63	18.0	15.6	10	10	30	30	30	30	25	25
10	7.51	24.1	20.8	8	10	40	35	60	60	35	30
12.5	9.39	30.1	26.1	8	8	50	45	60	60	45	35
15	11.3	36.1	31.3	8	8	60	50	60	60	50	45
17.5	13.1	42.1	36.5	6	8	70	60	100	60	60	50
20	15.0	48.1	41.7	6	6	80	70	100	100	70	60
22.5	16.9	54.1	46.9	4	6	90	80	100	100	80	70
25	18.8	60.1	52.1	4	4	100	90	100	100	90	70
27.5	20.7	66.2	57.3	3	4	125	100	200	100	90	80
30	22.5	72.2	62.5	3	4	125	100	200	100	100	90
35	26.3	84.2	73.0	2	3	150	125	200	200	125	100
40	30.0	96.2	83.4	1/0	2	175	150	200	200	150	125
45	33.8	108.3	93.8	1/0	1	200	150	200	200	150	150
50	37.6	120.3	104.2	2/0	1/0	200	175	200	200	175	150
60	45.1	144.3	125.1	3/0	2/0	250	200	400	200	200	175
70	52.6	168.4	145.9	4/0	3/0	300	250	400	400	250	200
75	56.3	180.4	156.4	250 MCM	4/0	300	250	400	400	250	200
80	60.1	192.5	166.8	300 MCM	4/0	350	300	400	400	300	250
90	67.6	216.5	187.6	350 MCM	250 MCM	400	300	400	400	300	250
100	75.1	240.6	208.5	400 MCM	300 MCM	400	350	400	400	350	300
125	93.9	300.7	260.6	(2) 4/0	(2) 2/0	500	450	600	600	450	350
150	112.7	360.8	312.7	(2) 250 MCM	(2) 4/0	600	500	600	600	500	450
175	131.4	421.0	364.9	(2) 300 MCM	(2) 250 MCM	700	600	800	600	600	500
200	150.2	481.1	417.0	(2) 400 MCM	(2) 350 MCM	800	700	800	800	700	600
225	169.0	541.3	469.1	(2) 500 MCM	(2) 400 MCM	900	800	1200	800	800	600
250	187.8	601.4	521.2	(3) 300 MCM	(2) 500 MCM	1000	900	1200	1200	900	700
275	206.6	661.5	573.4	(3) 350 MCM	(3) 300 MCM	1200	1000	1200	1200	900	800
300	225.3	721.7	625.5	(3) 400 MCM	(3) 300 MCM	1200	1000	1200	1200	1000	900

▲ Ampacity based on 135% rated capacitor current.
● Fuse rating based on 165% rated capacitor current for Class R time delay.
★ Switch rating based on 165% rated capacitor current.
■ Breaker rating based on 135% rated capacitor current.

TABLE 6
480 Volt 3Ø/60 Hertz

kvar Rating	Rated Current	Wire Size▲ 75°C Cu	Fuse● Amperes	Fusible Switch Amperes★	Molded Case Circuit Breaker Amperes■
2.5	3.0	14	5	30	15
5	6.0	14	10	30	15
7.5	9.0	14	15	30	15
10	12.0	12	20	30	20
12.5	15.0	10	25	30	25
15	18.0	10	30	30	25
17.5	21.0	10	35	60	30
20	24.1	8	40	60	35
22.5	27.1	8	45	60	40
25	30.1	8	50	60	45
27.5	33.1	8	60	60	45
30	36.1	8	60	60	50
35	42.1	6	70	100	60
40	48.1	6	80	100	70
45	54.1	4	90	100	80
50	60.1	4	100	100	90
60	72.2	3	125	200	100
70	84.2	2	150	200	125
75	90.2	1	150	200	125
80	96.2	1/0	175	200	150
90	108.3	1/0	200	200	150
100	120.3	2/0	200	200	175
125	150.4	4/0	250	400	225
150	180.4	250 MCM	300	400	250
175	210.5	300 MCM	350	400	300
200	240.6	(2) 2/0	400	400	350
225	270.6	(2) 3/0	450	600	400
250	300.7	(2) 4/0	500	600	450
275	330.8	(2) 4/0	600	600	450
300	360.8	(2) 250 MCM	600	600	500
325	390.9	(2) 300 MCM	700	800	600
350	421.0	(2) 300 MCM	700	800	600
375	451.1	(2) 350 MCM	800	800	700
400	481.1	(2) 400 MCM	800	800	700
425	511.2	(2) 500 MCM	900	1200	700
450	541.3	(2) 500 MCM	900	1200	800
475	571.3	(3) 300 MCM	1000	1200	800
500	601.4	(3) 300 MCM	1000	1200	900
525	631.5	(3) 300 MCM	1200	1200	900
550	661.5	(3) 350 MCM	1200	1200	900
575	691.6	(3) 400 MCM	1200	1200	1000
600	721.7	(3) 400 MCM	1200	1200	1000

▲ Ampacity based on 135% rated capacitor current.
● Fuse rating based on 165% rated capacitor current for Class R time delay.
★ Switch rating based on 165% rated capacitor current.
■ Breaker rating based on 135% rated capacitor current.

TABLE 7
600 Volt 3∅/60 Hertz

kvar Rating	Rated Current	Wire Size▲ 75°C Cu	Fuse● Amperes	Fusible Switch Amperes★	Molded Case Circuit Breaker Amperes■
2.5	2.4	14	5	30	10
5	4.8	14	10	30	15
7.5	7.2	14	15	30	15
10	9.6	14	20	30	15
12.5	12.0	12	25	30	20
15	14.4	12	30	30	20
17.5	16.8	10	30	30	25
20	19.2	10	35	60	30
22.5	21.7	10	40	60	30
25	24.1	8	40	60	35
27.5	26.5	8	45	60	40
30	28.9	8	50	60	40
35	33.7	8	60	60	50
40	38.5	6	70	100	60
45	43.3	6	80	100	60
50	48.1	6	80	100	70
60	57.7	4	100	100	80
70	67.4	3	125	200	100
75	72.2	3	125	200	100
80	77.0	2	150	200	125
90	86.6	1	150	200	125
100	96.2	1/0	175	200	150
125	120.3	2/0	200	200	175
150	144.3	3/0	250	400	200
175	168.4	4/0	300	400	250
200	192.5	300 MCM	350	400	300
225	216.5	350 MCM	400	400	300
250	240.6	400 MCM	400	400	350
275	264.6	500 MCM	450	600	400
300	288.7	(2) 3/0	500	600	400
325	312.7	(2) 4/0	600	600	450
350	336.8	(2) 4/0	600	600	500
375	360.8	(2) 250 MCM	600	600	500
400	384.9	(2) 300 MCM	800	800	600
425	409.0	(2) 300 MCM	800	800	600
450	433.0	(2) 350 MCM	800	800	600
475	457.1	(2) 350 MCM	800	800	700
500	481.1	(2) 400 MCM	800	800	700
525	505.2	(2) 500 MCM	900	1200	700
550	529.2	(2) 500 MCM	900	1200	800
575	553.3	(2) 500 MCM	1000	1200	800
600	577.4	(3) 300 MCM	1000	1200	800

▲Ampacity based on 135% rated capacitor current.
●Fuse rating based on 165% rated capacitor current for Class R time delay.
★Switch rating based on 165% rated capacitor current.
■Breaker rating based on 135% rated capacitor current.

Overcurrent Protection

Overcurrent protection for a capacitor is twofold; branch conductors must be protected against overcurrent and adequate protection must also be provided to prevent capacitor cell rupture resulting from internal arcing faults.

When internal capacitor fuses are selected for cell rupture protection, they must be able to withstand the relatively high inrush current associated with capacitor switching, carry rated current with an allowance for short time overload and transients, and detect and isolate faulted capacitor cells before internal gas pressures cause cell rupture. Unfortunately, this is often impossible or difficult to achieve. The result is usually a fuse which often opens when the capacitor is energized. Pressure sensitive interrupters on the other hand alleviate this problem since they respond only to internal gas pressure.

Article 460 of the NEC regarding capacitor **branch conductor** overcurrent protection states:

> An overcurrent device shall be provided in each ungrounded conductor for each capacitor bank. *Exception: A separate overcurrent device shall not be required for a capacitor connected on the load side of a motor overload protective device.*
>
> The rating or setting of the overcurrent device shall be as low as practicable.

The above exception pertains to capacitors installed as shown in Figure 9a.

In general, fuses should be rated between 165% to 250% of rated capacitor current to allow for tolerances and momentary surges. Molded case circuit breakers are generally selected at 135% rated current.

When a capacitor is located on the load side of a motor overload device (Figure 9a), the rating or setting of the device must be reduced to match the reduced line current of the motor-capacitor combination. Line current reduction in percent is given in Tables 2 and 3.

Switching

Regarding disconnecting means the NEC states:

> A disconnecting means shall be provided in each ungrounded conductor for each capacitor bank. *Exception: Where a capacitor is connected on the load side of a motor overload protective device.*

The disconnecting means shall open all ungrounded conductors simultaneously.

The disconnecting means shall be permitted to disconnect the capacitor from the line as a regular operating procedure. The rating or setting of the disconnecting means shall not be less than 135 percent of the rated current of the capacitor.

A separate disconnecting means is not required when the capacitor is located on the load side of a motor running overload device (Figure 9a). The rating for the safety switches shown in Tables 5, 6 and 7 are based on 165 percent rated current and 135 percent rated current for molded case circuit breakers.

Operating Characteristics

Voltage

The effective kvar output of a capacitor is dependent upon the applied voltage. The effective kvar output can be determined as follows:

$$\text{Effective kvar} = \text{rated kvar} \times \frac{\text{operating voltage}^2}{\text{rated voltage}^2}$$

Frequency

Like voltage, the effective kvar output of a capacitor is dependent upon operating frequency and can be determined as follows:

$$\text{Effective kvar} = \text{rated kvar} \times \frac{\text{operating frequency}}{\text{rated frequency}}$$

Useful Capacitor Formulas

Nomenclature:

C = capacitance in microfarads
Xc = capacitive reactance in ohms
f = frequency in cycles per second
fo = system resonant frequency
V = line voltage in volts
I = line current in amperes
kVA = kilovolt amperes
kVAsc = transformer short circuit kVA
kW = kilowatts
kvar = kilovars

Rated current:

$$I = \frac{\text{kvar} \times 1000}{\sqrt{3} \times V} \text{ (three phase)}$$

Capacitors in parallel:

$$C = C_1 + C_2 + C_3 \ldots + C_n$$

Capacitors in series:

$$C = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \ldots + \frac{1}{C_n}}$$

Capacitive reactance:

$$Xc = \frac{10^6}{(2fC)}$$

Rated kvar:

$$\text{kvar} = \frac{\sqrt{3} \times V \times I}{1000} \text{ (three phase)}$$

also,

$$\text{kvar} = \frac{(2fC)\,(kV)^2}{1000}$$

System Resonant Frequency:

$$fo = 60\sqrt{\frac{\text{kVAsc}}{\text{kVAR}}}$$

Standard References

(1) ANSI/IEEE Standard 18-1980, Shunt Power Capacitors
(2) IEEE Standard 141-1976, Recommended Practice for Electrical Power Distribution for Industrial Plants
(3) IEEE Standard 399-1980, Power System Analysis
(4) NEMA CP1-1979, Shunt Capacitors
(5) UL 810 Standard for Capacitors
(6) NFPA 70, National Electrical Code (1984)